

For Reference

---

**NOT TO BE TAKEN FROM THIS ROOM**

# For Reference

NOT TO BE TAKEN FROM THIS ROOM

Ex LIBRIS  
UNIVERSITATIS  
ALBERTAENSIS





## Regulations Regarding Theses and Dissertations

[illegible]







Digitized by the Internet Archive  
in 2019 with funding from  
University of Alberta Libraries

<https://archive.org/details/Pond1966>



1966(1)  
#136

THE UNIVERSITY OF ALBERTA

LEAN MIXTURES OF PROPANE AS A  
FUEL FOR INTERNAL COMBUSTION ENGINES

by

GERALD ROY POND, B. ENG. (NOVA SCOTIA TECHNICAL COLLEGE)

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES  
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR  
THE DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF MECHANICAL ENGINEERING

EDMONTON, ALBERTA

SEPTEMBER, 1966



THE UNIVERSITY OF CHICAGO

IN THE DEPARTMENT OF CHEMISTRY  
BY

JOHN EDGAR HOOVER

PH.D. THESIS  
SUBMITTED TO THE FACULTY OF THE DIVISION OF THE PHYSICAL SCIENCES  
IN CANDIDACY FOR THE DEGREE OF DOCTOR OF PHILOSOPHY  
BY

JOHN EDGAR HOOVER  
PH.D. THESIS  
SUBMITTED TO THE FACULTY OF THE DIVISION OF THE PHYSICAL SCIENCES  
IN CANDIDACY FOR THE DEGREE OF DOCTOR OF PHILOSOPHY  
BY

UNIVERSITY OF ALBERTA  
FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled, "LEAN MIXTURES OF PROPANE AS A FUEL FOR INTERNAL COMBUSTION ENGINES", submitted by GERALD ROY POND in partial fulfilment of the requirements for the degree of Master of Science.





ABSTRACT

The performance of a single-cylinder, low speed, spark ignition, internal combustion engine has been studied using lean (i.e. air-rich) mixtures of propane as the fuel. The power output and thermal efficiencies have been determined at various compression ratios and fuel-air ratios. A comparison is also made with the engine when burning gasoline.

Maximum operating fuel economy is obtained at a fuel-air ratio of 0.04 lb. of propane per lb. of air, regardless of the compression ratio. It is also shown that the overall performance of an engine may be improved by burning propane as the fuel at a higher compression ratio than burning gasoline at a lower CR.

A theoretical analysis is also shown for obtaining "cycle" temperatures, indicated thermal efficiency and brake mean effective pressure.

CHAPTER II

The first part of the book is devoted to a general survey of the history of the subject. It begins with a brief account of the early attempts to explain the origin of life, and then proceeds to a more detailed consideration of the various theories which have been advanced from time to time. The author discusses the views of the ancient philosophers, the medieval theologians, and the modern scientists, and shows how the subject has gradually become a branch of natural science.

The second part of the book is devoted to a detailed examination of the various theories which have been advanced to explain the origin of life. The author discusses the views of the ancient philosophers, the medieval theologians, and the modern scientists, and shows how the subject has gradually become a branch of natural science. He then proceeds to a more detailed consideration of the various theories which have been advanced from time to time. The author discusses the views of the ancient philosophers, the medieval theologians, and the modern scientists, and shows how the subject has gradually become a branch of natural science.

### ACKNOWLEDGEMENTS

The author wishes to thank the following for their contributions:

- Prof. D. Panar for suggesting an interesting topic and for his supervision during the research and writing of the thesis.
- Du Pont of Canada Ltd., for personal financial assistance provided through a Grant to the Department of Mechanical Engineering.
- The National Research Council for the funds made available under Grant No. A-2767, for the research equipment.
- my wife, Thelma, and daughters for their understanding and patience during my absence.
- Miss Lynne Fiveland and Mrs. Cathy Arial for typing the thesis.



THE HISTORY OF THE

THE HISTORY OF THE

THE HISTORY OF THE

THE HISTORY OF THE

THE HISTORY OF THE

THE HISTORY OF THE

THE HISTORY OF THE

# TABLE OF CONTENTS

	<u>Page</u>
CHAPTER I <u>INTRODUCTION</u> .....	1
1.1 History.....	1
1.1-1 Theoretical Cycles.....	1
1.1-2 Experimental Work.....	6
CHAPTER II <u>THEORETICAL ANALYSIS</u>	
2.1 Governing Equations.....	6
2.1-1 Otto Air-Standard Cycle.....	6
2.1-2 Otto Fuel-Air Cycle.....	8
2.2 Analysis using Propane.....	9
CHAPTER III <u>EXPERIMENTAL WORK</u> .....	25
3.1 Equipment.....	25
3.2 Experimental Methods.....	26
3.2-1 Test Procedure.....	26
3.2-2 Calculations.....	30
CHAPTER IV <u>RESULTS</u> .....	36
4.1 Experimental Results.....	36
4.2 Results of Theoretical Analysis.....	39
CHAPTER V <u>DISCUSSION OF RESULTS</u> .....	47
5.1 General.....	47
5.2 Comparison of Experimental and Theoretical Results.....	48

# REPORT

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35

1. The purpose of this report is to provide a comprehensive overview of the project's progress and results. The report is organized into several sections, each detailing a different aspect of the project.

2. The first section, titled "Introduction", provides a brief overview of the project's goals and objectives. It also discusses the importance of the project and the role of the report in the overall project management process.

3. The second section, titled "Methodology", describes the methods and techniques used in the project. This section includes a detailed description of the data collection process, the analysis methods used, and the tools and software used in the project.

4. The third section, titled "Results", presents the findings of the project. This section includes a detailed description of the data collected, the results of the analysis, and the conclusions drawn from the data.

5. The fourth section, titled "Discussion", discusses the implications of the results and the conclusions drawn from the data. This section also includes a discussion of the limitations of the study and the need for further research.

6. The fifth section, titled "Conclusion", summarizes the key findings of the project and provides a final overview of the project's progress and results.

7. The sixth section, titled "References", lists the sources of information used in the project. This section includes a list of books, articles, and other sources of information that were consulted during the project.

8. The seventh section, titled "Appendix", contains additional information that is relevant to the project. This section includes a list of figures, tables, and other data that are not included in the main body of the report.

9. The eighth section, titled "Index", provides a list of the topics covered in the report. This section is useful for readers who want to find specific information quickly and easily.

10. The ninth section, titled "Glossary", defines the terms and abbreviations used in the report. This section is useful for readers who are unfamiliar with the terminology used in the project.

11. The tenth section, titled "Bibliography", lists the sources of information used in the project. This section includes a list of books, articles, and other sources of information that were consulted during the project.

12. The eleventh section, titled "List of Figures", provides a list of the figures included in the report. This section is useful for readers who want to find specific figures quickly and easily.

13. The twelfth section, titled "List of Tables", provides a list of the tables included in the report. This section is useful for readers who want to find specific tables quickly and easily.

14. The thirteenth section, titled "List of Abbreviations", provides a list of the abbreviations used in the report. This section is useful for readers who want to find the full names of the abbreviations quickly and easily.

15. The fourteenth section, titled "List of Symbols", provides a list of the symbols used in the report. This section is useful for readers who want to find the meaning of the symbols quickly and easily.

16. The fifteenth section, titled "List of Equations", provides a list of the equations used in the report. This section is useful for readers who want to find the meaning of the equations quickly and easily.

17. The sixteenth section, titled "List of Figures", provides a list of the figures included in the report. This section is useful for readers who want to find specific figures quickly and easily.

18. The seventeenth section, titled "List of Tables", provides a list of the tables included in the report. This section is useful for readers who want to find specific tables quickly and easily.

19. The eighteenth section, titled "List of Abbreviations", provides a list of the abbreviations used in the report. This section is useful for readers who want to find the full names of the abbreviations quickly and easily.

20. The nineteenth section, titled "List of Symbols", provides a list of the symbols used in the report. This section is useful for readers who want to find the meaning of the symbols quickly and easily.

21. The twentieth section, titled "List of Equations", provides a list of the equations used in the report. This section is useful for readers who want to find the meaning of the equations quickly and easily.

22. The twenty-first section, titled "List of Figures", provides a list of the figures included in the report. This section is useful for readers who want to find specific figures quickly and easily.

23. The twenty-second section, titled "List of Tables", provides a list of the tables included in the report. This section is useful for readers who want to find specific tables quickly and easily.

24. The twenty-third section, titled "List of Abbreviations", provides a list of the abbreviations used in the report. This section is useful for readers who want to find the full names of the abbreviations quickly and easily.

25. The twenty-fourth section, titled "List of Symbols", provides a list of the symbols used in the report. This section is useful for readers who want to find the meaning of the symbols quickly and easily.

26. The twenty-fifth section, titled "List of Equations", provides a list of the equations used in the report. This section is useful for readers who want to find the meaning of the equations quickly and easily.

27. The twenty-sixth section, titled "List of Figures", provides a list of the figures included in the report. This section is useful for readers who want to find specific figures quickly and easily.

28. The twenty-seventh section, titled "List of Tables", provides a list of the tables included in the report. This section is useful for readers who want to find specific tables quickly and easily.

29. The twenty-eighth section, titled "List of Abbreviations", provides a list of the abbreviations used in the report. This section is useful for readers who want to find the full names of the abbreviations quickly and easily.

30. The twenty-ninth section, titled "List of Symbols", provides a list of the symbols used in the report. This section is useful for readers who want to find the meaning of the symbols quickly and easily.

31. The thirtieth section, titled "List of Equations", provides a list of the equations used in the report. This section is useful for readers who want to find the meaning of the equations quickly and easily.

32. The thirty-first section, titled "List of Figures", provides a list of the figures included in the report. This section is useful for readers who want to find specific figures quickly and easily.

33. The thirty-second section, titled "List of Tables", provides a list of the tables included in the report. This section is useful for readers who want to find specific tables quickly and easily.

34. The thirty-third section, titled "List of Abbreviations", provides a list of the abbreviations used in the report. This section is useful for readers who want to find the full names of the abbreviations quickly and easily.

35. The thirty-fourth section, titled "List of Symbols", provides a list of the symbols used in the report. This section is useful for readers who want to find the meaning of the symbols quickly and easily.

35. The thirty-fifth section, titled "List of Equations", provides a list of the equations used in the report. This section is useful for readers who want to find the meaning of the equations quickly and easily.

	<u>Page</u>
5.3 Experimental Error.....	49
5.4 Miscellaneous Observations.....	50
CHAPTER VI <u>CONCLUSIONS AND RECOMMENDATIONS</u> .....	52
6.1 Conclusions.....	52
6.2 Applications.....	54
6.3 Recommendations.....	55
<u>REFERENCES</u> .....	56
<u>BIBLIOGRAPHY</u> .....	57
APPENDIX A - Sample Theoretical Calculation.....	58
APPENDIX B - Program for Theoretical Analysis.....	82
APPENDIX C - Sample Set of Test Data.....	93
APPENDIX D - Sample Calculation of Test Data.....	94
APPENDIX E - Program for Calculations of Test Data.....	98
APPENDIX F - Sample Set of Results as Calculated by Program.....	106





## LIST OF FIGURES

<u>FIGURE</u>	<u>PAGE</u>
2.1 P-V and T-S Diagrams of Otto Air Cycle.....	6
2.2 Actual Fuel-Air Cycle Losses.....	10
3.1 CFR-Engine and Test Equipment.....	27
3.2 Control Panel.....	28
3.3 Mild Steel Exhaust Valve.....	28
4.1 Indicated Mean Effective Pressure versus Fuel-Air Ratio.....	40
4.2 Indicated Thermal Efficiency versus Fuel-Air Ratio..	41
4.3 Brake Thermal Efficiency versus Fuel-Air Ratio.....	42
4.4 "Comparative Fuel Consumption Loops".....	43
4.5 Theoretical Indicated Thermal Efficiency.....	44
4.6 Theoretical Mean Effective Pressure.....	45
4.7 Adiabatic Flame Temperature.....	46

## LIST OF TABLES

<u>TABLE</u>	<u>PAGE</u>
4.1 Experimental Results.....	38



NOMENCLATURE

I.C.	Internal combustion
L.P.	Liquified petroleum
P	Pressure
V	Volume
T	Temperature
S	Entropy
Net W	Net work
$Q_{in}$	Heat in
$Q_{out}$	Heat out
m	Mass
$C_p$	Specific Heat at constant pressure
$C_v$	Specific Heat at constant volume
B.T.U.	British Thermal Units
$\eta$	Thermal efficiency
k	Ratio of specific heats
CR	Compression ratio
$C_3H_8$	Propane gas
$O_2$	Oxygen
$N_2$	Nitrogen
$CO_2$	Carbon Dioxide
CO	Carbon Monoxide
$H_2O$	Water Vapor
f	Fraction of residual gases remaining in the engine cylinder

1	1000000	1000000
2	1000000	1000000
3	1000000	1000000
4	1000000	1000000
5	1000000	1000000
6	1000000	1000000
7	1000000	1000000
8	1000000	1000000
9	1000000	1000000
10	1000000	1000000
11	1000000	1000000
12	1000000	1000000
13	1000000	1000000
14	1000000	1000000
15	1000000	1000000
16	1000000	1000000
17	1000000	1000000
18	1000000	1000000
19	1000000	1000000
20	1000000	1000000
21	1000000	1000000
22	1000000	1000000
23	1000000	1000000
24	1000000	1000000
25	1000000	1000000
26	1000000	1000000
27	1000000	1000000
28	1000000	1000000
29	1000000	1000000
30	1000000	1000000
31	1000000	1000000
32	1000000	1000000
33	1000000	1000000
34	1000000	1000000
35	1000000	1000000
36	1000000	1000000
37	1000000	1000000
38	1000000	1000000
39	1000000	1000000
40	1000000	1000000
41	1000000	1000000
42	1000000	1000000
43	1000000	1000000
44	1000000	1000000
45	1000000	1000000
46	1000000	1000000
47	1000000	1000000
48	1000000	1000000
49	1000000	1000000
50	1000000	1000000
51	1000000	1000000
52	1000000	1000000
53	1000000	1000000
54	1000000	1000000
55	1000000	1000000
56	1000000	1000000
57	1000000	1000000
58	1000000	1000000
59	1000000	1000000
60	1000000	1000000
61	1000000	1000000
62	1000000	1000000
63	1000000	1000000
64	1000000	1000000
65	1000000	1000000
66	1000000	1000000
67	1000000	1000000
68	1000000	1000000
69	1000000	1000000
70	1000000	1000000
71	1000000	1000000
72	1000000	1000000
73	1000000	1000000
74	1000000	1000000
75	1000000	1000000
76	1000000	1000000
77	1000000	1000000
78	1000000	1000000
79	1000000	1000000
80	1000000	1000000
81	1000000	1000000
82	1000000	1000000
83	1000000	1000000
84	1000000	1000000
85	1000000	1000000
86	1000000	1000000
87	1000000	1000000
88	1000000	1000000
89	1000000	1000000
90	1000000	1000000
91	1000000	1000000
92	1000000	1000000
93	1000000	1000000
94	1000000	1000000
95	1000000	1000000
96	1000000	1000000
97	1000000	1000000
98	1000000	1000000
99	1000000	1000000
100	1000000	1000000

U	Internal energy
H	Enthalpy
J	Conversion factor (778 ft-lb/BTU)
M	No. of moles
R	Universal Gas Constant (1545 ft-lb/lb-mole <sup>°F</sup> or 1.986 BTU/lb-mole <sup>°R</sup> )
ln	Logarithm to base e
x	Fraction of CO <sub>2</sub> dissociated
y	Fraction of H <sub>2</sub> O        //
G	Gibb's function
a	Moles of constituent A
b	Moles of constituent B
c	Moles of constituent C
d	Moles of constituent D
K <sub>p</sub>	Pressure equilibrium constant
CE	Chemical energy
L.H.V.	Lower Heating Value of the fuel
u	Energy per mole
$\phi_p$	$m \int \frac{C_p}{T} dt$
m.e.p.	Mean effective pressure
r.p.m.	Revolutions per minute
S.A.E.	Society of Automotive Engineers
in.	Inches
Hg.	Mercury
°F	Degrees Fahrenheit



1. General Fund	100
2. Special Fund	100
3. Capital Fund	100
4. Debt Service Fund	100
5. Reserve Fund	100
6. Unassigned Fund	100
7. Other Fund	100
8. Total	100
9. General Fund	100
10. Special Fund	100
11. Capital Fund	100
12. Debt Service Fund	100
13. Reserve Fund	100
14. Unassigned Fund	100
15. Other Fund	100
16. Total	100
17. General Fund	100
18. Special Fund	100
19. Capital Fund	100
20. Debt Service Fund	100
21. Reserve Fund	100
22. Unassigned Fund	100
23. Other Fund	100
24. Total	100
25. General Fund	100
26. Special Fund	100
27. Capital Fund	100
28. Debt Service Fund	100
29. Reserve Fund	100
30. Unassigned Fund	100
31. Other Fund	100
32. Total	100
33. General Fund	100
34. Special Fund	100
35. Capital Fund	100
36. Debt Service Fund	100
37. Reserve Fund	100
38. Unassigned Fund	100
39. Other Fund	100
40. Total	100
41. General Fund	100
42. Special Fund	100
43. Capital Fund	100
44. Debt Service Fund	100
45. Reserve Fund	100
46. Unassigned Fund	100
47. Other Fund	100
48. Total	100
49. General Fund	100
50. Special Fund	100
51. Capital Fund	100
52. Debt Service Fund	100
53. Reserve Fund	100
54. Unassigned Fund	100
55. Other Fund	100
56. Total	100
57. General Fund	100
58. Special Fund	100
59. Capital Fund	100
60. Debt Service Fund	100
61. Reserve Fund	100
62. Unassigned Fund	100
63. Other Fund	100
64. Total	100
65. General Fund	100
66. Special Fund	100
67. Capital Fund	100
68. Debt Service Fund	100
69. Reserve Fund	100
70. Unassigned Fund	100
71. Other Fund	100
72. Total	100
73. General Fund	100
74. Special Fund	100
75. Capital Fund	100
76. Debt Service Fund	100
77. Reserve Fund	100
78. Unassigned Fund	100
79. Other Fund	100
80. Total	100
81. General Fund	100
82. Special Fund	100
83. Capital Fund	100
84. Debt Service Fund	100
85. Reserve Fund	100
86. Unassigned Fund	100
87. Other Fund	100
88. Total	100
89. General Fund	100
90. Special Fund	100
91. Capital Fund	100
92. Debt Service Fund	100
93. Reserve Fund	100
94. Unassigned Fund	100
95. Other Fund	100
96. Total	100
97. General Fund	100
98. Special Fund	100
99. Capital Fund	100
100. Debt Service Fund	100
101. Reserve Fund	100
102. Unassigned Fund	100
103. Other Fund	100
104. Total	100
105. General Fund	100
106. Special Fund	100
107. Capital Fund	100
108. Debt Service Fund	100
109. Reserve Fund	100
110. Unassigned Fund	100
111. Other Fund	100
112. Total	100
113. General Fund	100
114. Special Fund	100
115. Capital Fund	100
116. Debt Service Fund	100
117. Reserve Fund	100
118. Unassigned Fund	100
119. Other Fund	100
120. Total	100
121. General Fund	100
122. Special Fund	100
123. Capital Fund	100
124. Debt Service Fund	100
125. Reserve Fund	100
126. Unassigned Fund	100
127. Other Fund	100
128. Total	100
129. General Fund	100
130. Special Fund	100
131. Capital Fund	100
132. Debt Service Fund	100
133. Reserve Fund	100
134. Unassigned Fund	100
135. Other Fund	100
136. Total	100
137. General Fund	100
138. Special Fund	100
139. Capital Fund	100
140. Debt Service Fund	100
141. Reserve Fund	100
142. Unassigned Fund	100
143. Other Fund	100
144. Total	100
145. General Fund	100
146. Special Fund	100
147. Capital Fund	100
148. Debt Service Fund	100
149. Reserve Fund	100
150. Unassigned Fund	100
151. Other Fund	100
152. Total	100
153. General Fund	100
154. Special Fund	100
155. Capital Fund	100
156. Debt Service Fund	100
157. Reserve Fund	100
158. Unassigned Fund	100
159. Other Fund	100
160. Total	100
161. General Fund	100
162. Special Fund	100
163. Capital Fund	100
164. Debt Service Fund	100
165. Reserve Fund	100
166. Unassigned Fund	100
167. Other Fund	100
168. Total	100
169. General Fund	100
170. Special Fund	100
171. Capital Fund	100
172. Debt Service Fund	100
173. Reserve Fund	100
174. Unassigned Fund	100
175. Other Fund	100
176. Total	100
177. General Fund	100
178. Special Fund	100
179. Capital Fund	100
180. Debt Service Fund	100
181. Reserve Fund	100
182. Unassigned Fund	100
183. Other Fund	100
184. Total	100
185. General Fund	100
186. Special Fund	100
187. Capital Fund	100
188. Debt Service Fund	100
189. Reserve Fund	100
190. Unassigned Fund	100
191. Other Fund	100
192. Total	100
193. General Fund	100
194. Special Fund	100
195. Capital Fund	100
196. Debt Service Fund	100
197. Reserve Fund	100
198. Unassigned Fund	100
199. Other Fund	100
200. Total	100

CF	Correction factor
Bar. Pres.	Barometric pressure
$P_t$	Total gas pressure
$P_{sat}$	Saturation pressure of water
$T_{st}$	Standard temperature (520°R)
BHP	Brake Horsepower
FHP	Friction Horsepower
IHP	Indicated Horsepower
CIHP	Corrected Indicated Horsepower (to S.A.E. Standard atmosphere )
CBHP	Corrected Brake Horsepower
Mech. Eff.	Mechanical efficiency
IMEP	Indicated Mean Effective Pressure
C	Orifice coefficient

General Information	(1)
Expenditure Information	(2)
Expenditure Item Detail	(3)
General Information	(4)
Expenditure Information	(5)
Expenditure Item Detail	(6)
General Information	(7)
Expenditure Information	(8)
Expenditure Item Detail	(9)
General Information	(10)
Expenditure Information	(11)
Expenditure Item Detail	(12)
General Information	(13)
Expenditure Information	(14)
Expenditure Item Detail	(15)
General Information	(16)
Expenditure Information	(17)
Expenditure Item Detail	(18)
General Information	(19)
Expenditure Information	(20)
Expenditure Item Detail	(21)
General Information	(22)
Expenditure Information	(23)
Expenditure Item Detail	(24)
General Information	(25)
Expenditure Information	(26)
Expenditure Item Detail	(27)
General Information	(28)
Expenditure Information	(29)
Expenditure Item Detail	(30)
General Information	(31)
Expenditure Information	(32)
Expenditure Item Detail	(33)
General Information	(34)
Expenditure Information	(35)
Expenditure Item Detail	(36)
General Information	(37)
Expenditure Information	(38)
Expenditure Item Detail	(39)
General Information	(40)
Expenditure Information	(41)
Expenditure Item Detail	(42)
General Information	(43)
Expenditure Information	(44)
Expenditure Item Detail	(45)
General Information	(46)
Expenditure Information	(47)
Expenditure Item Detail	(48)
General Information	(49)
Expenditure Information	(50)
Expenditure Item Detail	(51)
General Information	(52)
Expenditure Information	(53)
Expenditure Item Detail	(54)
General Information	(55)
Expenditure Information	(56)
Expenditure Item Detail	(57)
General Information	(58)
Expenditure Information	(59)
Expenditure Item Detail	(60)
General Information	(61)
Expenditure Information	(62)
Expenditure Item Detail	(63)
General Information	(64)
Expenditure Information	(65)
Expenditure Item Detail	(66)
General Information	(67)
Expenditure Information	(68)
Expenditure Item Detail	(69)
General Information	(70)
Expenditure Information	(71)
Expenditure Item Detail	(72)
General Information	(73)
Expenditure Information	(74)
Expenditure Item Detail	(75)
General Information	(76)
Expenditure Information	(77)
Expenditure Item Detail	(78)
General Information	(79)
Expenditure Information	(80)
Expenditure Item Detail	(81)
General Information	(82)
Expenditure Information	(83)
Expenditure Item Detail	(84)
General Information	(85)
Expenditure Information	(86)
Expenditure Item Detail	(87)
General Information	(88)
Expenditure Information	(89)
Expenditure Item Detail	(90)
General Information	(91)
Expenditure Information	(92)
Expenditure Item Detail	(93)
General Information	(94)
Expenditure Information	(95)
Expenditure Item Detail	(96)
General Information	(97)
Expenditure Information	(98)
Expenditure Item Detail	(99)
General Information	(100)

# CHAPTER I

## INTRODUCTION

The fundamental problem considered in this investigation is the experimental determination of the effects of lean fuel-air ratios of gaseous propane ( $C_3H_8$ ) when used as a fuel in a spark ignition four-cycle internal combustion engine.

### 1.1 HISTORY

The spark ignition four-cycle reciprocating internal combustion engine cycle is usually referred to as the Otto cycle, after N.A. Otto who is believed to have made the first successful internal combustion engine in about 1876.

A detailed explanation of the ideal Otto cycle and deviations from the ideal cycle are given in Chapter II.

#### 1.1-1 Theoretical Cycles

Goodenough and Baker [1]\* improved the understanding of internal-combustion engine analysis by considering actual mixtures of gasoline, clearance gases, variable

---

\* Numbers in square parenthesis designate References on page 56 .

# THE SOCIETY

The Society is a non-profit organization that is dedicated to the promotion of the arts and the advancement of the community. It was founded in 1980 and has since then been a leading force in the cultural and social life of the city.

For more information, please contact:

John Doe, President

123 Main Street, Suite 100, New York, NY 10001

Phone: (212) 555-1234  
Fax: (212) 555-5678  
Email: info@society.org  
Website: www.society.org

© 2000 The Society. All rights reserved.

Printed on recycled paper with soy-based inks.

For a complete list of our programs and services, please visit our website.

Thank you for your support and contribution.

The Society is a 501(c)(3) organization. All contributions are tax-deductible.

For more information, please contact our Development Office.

Phone: (212) 555-9010  
Fax: (212) 555-9011  
Email: development@society.org

www.society.org

For a complete list of our programs and services, please visit our website.

Page 1 of 1



specific heats and chemical equilibrium. Keenan and Kaye [2] prepared a set of highly accurate gas tables giving the thermodynamic properties of air and the combustion products of octane for fuel-air ratios of 25 and 50 percent of air for complete combustion at low temperatures i.e. they did not consider the dissociation of  $\text{CO}_2$  and  $\text{H}_2\text{O}$ . Hottel, Williams and Satterfield [3] presented a series of charts for hydrocarbon-air combustion. Charts are given for fuel expressed as  $\text{C}_n\text{H}_{2n}$  for six fuel-air ratios, ranging from 80 percent to 150 percent required fuel.

A theoretical analysis, using propane as the fuel is presented in Chapter II.

### 1.1-2 Experimental Work

During the past several decades numerous experimental analyses have been conducted on spark-ignition internal combustion engines, using various fuels, but mainly gasoline, the most commonly used fuel in a practical engine. The prime objective of any engine is power output and since this is in direct proportion to the number of cylinders, mean effective pressures, length of stroke, area of cylinder and number of revolutions per minute, an increase in any one of these for a particular fuel will result in a power increase. Practical considerations however limit the number of cylinders and size of cylinders. Increasing



the speed will increase the power output, up to an optimum value. However, prior to this the effect of speed increase has been to cause the efficiency to be reduced. The greatest possibility for increase of horsepower per unit of engine weight lies in increasing the mean effective pressure.

The most obvious way to increase the mean effective pressure is to increase the compression ratio of the engine. For a particular fuel, however, there is a maximum compression ratio above which the fuel will detonate (Engine Knock). Detonation results in a loss of power and if severe, the engine will be damaged. Many factors determine when a particular fuel will knock. Some of these factors are combustion chamber design, engine speed, spark timing, cylinder temperature, air-fuel ratio and air-fuel mixture temperature. Gasoline with knock inhibitors are now available which will allow engines to operate without knock at a higher compression ratio than if the gasoline were used without the inhibitor. Many investigations have been conducted regarding Engine Knock [4, 5, 6, 7].

Propane has a higher detonation resistance than all but the most expensive aviation gasoline. Propane also has the other characteristics necessary for a fuel in an I.C. engine i.e. adequate volatility without pre-heating, low sulphur content, has high heating value,





readily available at an economical cost, and the added advantage over gasoline in that its combustion is more complete [8]. Thus carbon deposits in the combustion chamber, and on the valves and piston head are notably reduced resulting in less dirty engine oil, resulting in fewer oil changes and less engine wear. There is also a reduction in the noxious exhaust odors, smoke and soot. Another advantage of propane is that it has a slow rate of flame travel during combustion, resulting in a decrease in peak pressure but resulting in an increase in mean effective pressure.

Operating variables such as spark advance, exhaust pressure, inlet pressure, inlet mixture temperature also have an influence on the mean effective pressure and the engine efficiency. A very thorough comparison of the effects of these variables is shown in Taylor [9].

The heating value of a fuel is not in direct proportion to the power output which can be obtained from the use of that fuel in a particular engine because of other factors which affect the power output. The heating value is, however, a direct measure of the quantity of fuel required; the higher the heat value the less fuel needed to do the same work. Propane has a slightly higher heating value per pound than gasoline but a lower value if compared on a volume basis.





Adams and Boldt [10] conducted extensive tests on three industrial engines, including one engine at three compression ratios using gasoline and liquified petroleum gas (Butane-propane). They found that at a given compression ratio, the engines developed 3-1/2 - 5% less power at high speeds on L.P.-gas than on gasoline. However compared to gasoline the L.P.-gas reduced brake specific fuel consumption on a mass basis up to 12% at low speeds. At high speeds fuel consumption was reduced by 0 - 9%. On a volume basis, the L.P. gas consumption increased due to the lower specific weight of the L.P.-gas. They also found that increasing the compression ratio from 7.5 to 11.5 increased the power 12% and reduced the brake specific fuel consumption by 11%.

Because of the certain advantages of propane as a fuel for internal combustion engines it is the purpose of this thesis to obtain data on an engine operating at maximum economy fuel-air ratio. Although this fuel-air ratio is at a lower than maximum power such information is necessary and of importance for vehicles when operating at cruising speed and is also very important to the designer and owner of stationary engines wishing to operate at maximum economy over an extended period of time.

# THE HISTORY OF THE UNITED STATES

The history of the United States is a story of a people who have grown from a small colony of English settlers to a great nation of free men and women. The story begins in 1492 when Christopher Columbus discovered the New World. The first English settlers came to the United States in 1607. They were the first of many waves of immigrants who came to the United States in search of a better life. The United States has a long and rich history of freedom and democracy. The United States has been a leader in the world for many years. The United States has a great future ahead of it.

The United States has a long and rich history of freedom and democracy. The United States has been a leader in the world for many years. The United States has a great future ahead of it.

The United States has a long and rich history of freedom and democracy. The United States has been a leader in the world for many years. The United States has a great future ahead of it.

The United States has a long and rich history of freedom and democracy. The United States has been a leader in the world for many years. The United States has a great future ahead of it.

The United States has a long and rich history of freedom and democracy. The United States has been a leader in the world for many years. The United States has a great future ahead of it.

The United States has a long and rich history of freedom and democracy. The United States has been a leader in the world for many years. The United States has a great future ahead of it.

The United States has a long and rich history of freedom and democracy. The United States has been a leader in the world for many years. The United States has a great future ahead of it.

## CHAPTER II

### THEORETICAL ANALYSIS

#### 2.1 GOVERNING EQUATIONS

##### 2.1-1 Otto Air-Standard Cycle

The simplest and crudest analysis of the Otto cycle considers the working medium as air or at least a gas having the properties of air. It is further assumed that the air has a constant specific heat.

This cycle is shown on the P-V and T-S diagrams of Fig. 2.1.

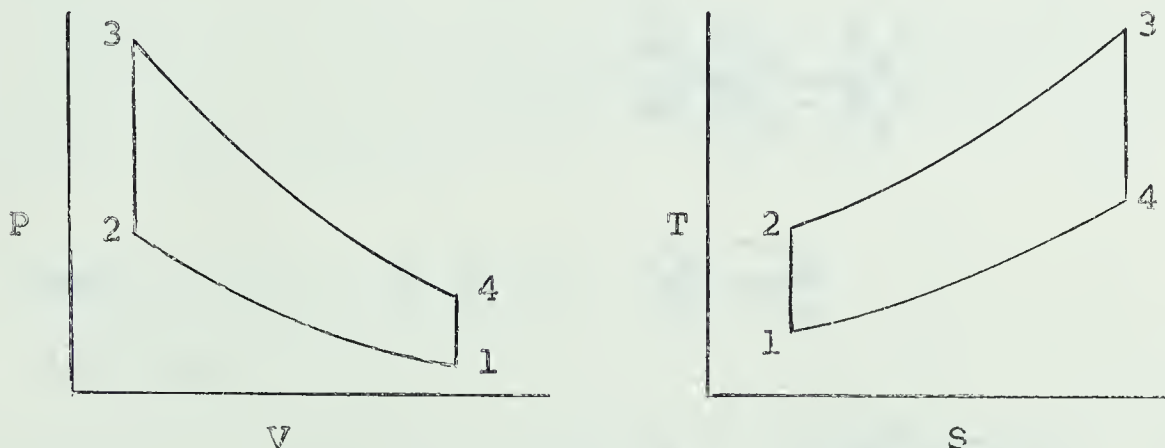


FIG. 2.1 OTTO CYCLE

The medium is compressed reversibly and adiabatically, i.e. isentropically, process 1-2. Heat is added at constant volume, process 2-3, while the piston is momentarily at rest at "top-dead center". Ignition occurs prior to point 3 in the actual engine. Isentropic expansion takes place, process 3-4, and process 4-1 is the rejection of heat while the piston is returning to its initial position at "bottom-dead center".





From the First Law of Thermodynamics for a closed system and assuming no changes in kinetic, potential or chemical energies and assuming adiabatic compression and expansion the net work of the system may be obtained from:

$$\text{Net } W = Q_{\text{in}} - Q_{\text{out}}$$

where  $Q_{\text{in}} = mc_v (T_3 - T_2)$  and  $Q_{\text{out}} = mc_v (T_4 - T_1)$

The thermal efficiency  $(\eta) = \frac{\text{net } W}{Q_{\text{in}}}$

therefore  $\eta = \frac{Q_{\text{in}} - Q_{\text{out}}}{Q_{\text{in}}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}} \quad (2.1)$

$$= 1 - \frac{mc_v (T_4 - T_1)}{mc_v (T_3 - T_2)}$$

so  $\eta = 1 - \frac{T_4 - T_1}{T_3 - T_2} \quad (2.2)$

$$= 1 - \frac{T_1}{T_2} \cdot \left( \frac{T_4/T_1 - 1}{T_3/T_2 - 1} \right)$$

But from isentropic relationships

$$\frac{T_4}{T_3} = \left( \frac{V_3}{V_4} \right)^{k-1} = \left( \frac{V_2}{V_1} \right)^{k-1} = \frac{T_1}{T_2}$$

$$\therefore \frac{T_4}{T_1} = \frac{T_3}{T_2}$$





so 
$$\eta = 1 - \frac{T_1}{T_2} = 1 - \left( \frac{V_2}{V_1} \right)^{k-1}$$

But 
$$\frac{V_1}{V_2} = \frac{V_4}{V_3} = \text{CR (Compression ratio)}.$$

$$\therefore \eta = 1 - \text{CR}^{1-k} \quad (2.3)$$

Thus in the air-standard Otto cycle the thermal efficiency is a function of only the compression ratio and the efficiency may be increased by increasing the compression ratio. Although the thermal efficiency will increase to a maximum value of one as CR increases, the rate of increase of  $\eta$  decreases as CR increases, and any increase is practically insignificant as the CR approaches 15 or 20.

## 2.1-2 Otto Fuel-Air Cycle

The spark-ignition engine deviates from the air-standard cycle in many ways. Some of the more important ways are as follows:

1. The medium consists of a mixture of fuel, air and residual gases.
2. The specific heats of the individual gases are different and vary with temperature.
3. The combustion process replaces the heat transfer process. Combustion takes time and is thus initiated before top-dead center.



4. After combustion, i.e. during adiabatic expansion and exhaust, the medium is no longer a mixture of fuel and air but air and products of combustion.
5. The reaction may not be complete.

The fuel-air cycle is an idealized thermodynamic process resembling what is occurring in an "ideal" engine because in a real engine the process is not cyclic in the thermodynamic sense.

Further deviations take place in the actual engine due to:

1. The inlet and exhaust processes will result in a pressure drop through the valves thus resulting in a loss of work.
2. The piston must do work on the mixture to get it out of the cylinder and this is more than the work done in the cylinder by the mixture at intake, resulting in a net loss of work.
3. Heat transfer is involved, so the compression and expansion processes are not isentropic, as assumed.

Fig. 2.2 illustrates the deviation of the actual cycle from the ideal cycle as it affects the P-V diagram.

## 2.2 ANALYSIS USING PROPANE

The reaction equation for propane reacting with the

The first part of the paper is devoted to the study of the properties of the function  $f(x)$  defined by the equation  $f(x) = \int_0^x f(t) dt$ . It is shown that  $f(x)$  is a constant function, and its value is determined by the initial condition  $f(0) = 1$ .

In the second part, we consider the problem of finding the maximum value of the function  $f(x)$  on the interval  $[0, 1]$ . It is shown that the maximum value is attained at  $x = 0$  and is equal to 1. This result is obtained by using the properties of the function  $f(x)$  and the fact that  $f(x) \leq 1$  for all  $x$  in the interval  $[0, 1]$ .

The third part of the paper is devoted to the study of the properties of the function  $f(x)$  defined by the equation  $f(x) = \int_0^x f(t) dt$ . It is shown that  $f(x)$  is a constant function, and its value is determined by the initial condition  $f(0) = 1$ . This result is obtained by using the properties of the function  $f(x)$  and the fact that  $f(x) \leq 1$  for all  $x$  in the interval  $[0, 1]$ .

In the fourth part, we consider the problem of finding the maximum value of the function  $f(x)$  on the interval  $[0, 1]$ . It is shown that the maximum value is attained at  $x = 0$  and is equal to 1. This result is obtained by using the properties of the function  $f(x)$  and the fact that  $f(x) \leq 1$  for all  $x$  in the interval  $[0, 1]$ .

The fifth part of the paper is devoted to the study of the properties of the function  $f(x)$  defined by the equation  $f(x) = \int_0^x f(t) dt$ . It is shown that  $f(x)$  is a constant function, and its value is determined by the initial condition  $f(0) = 1$ .

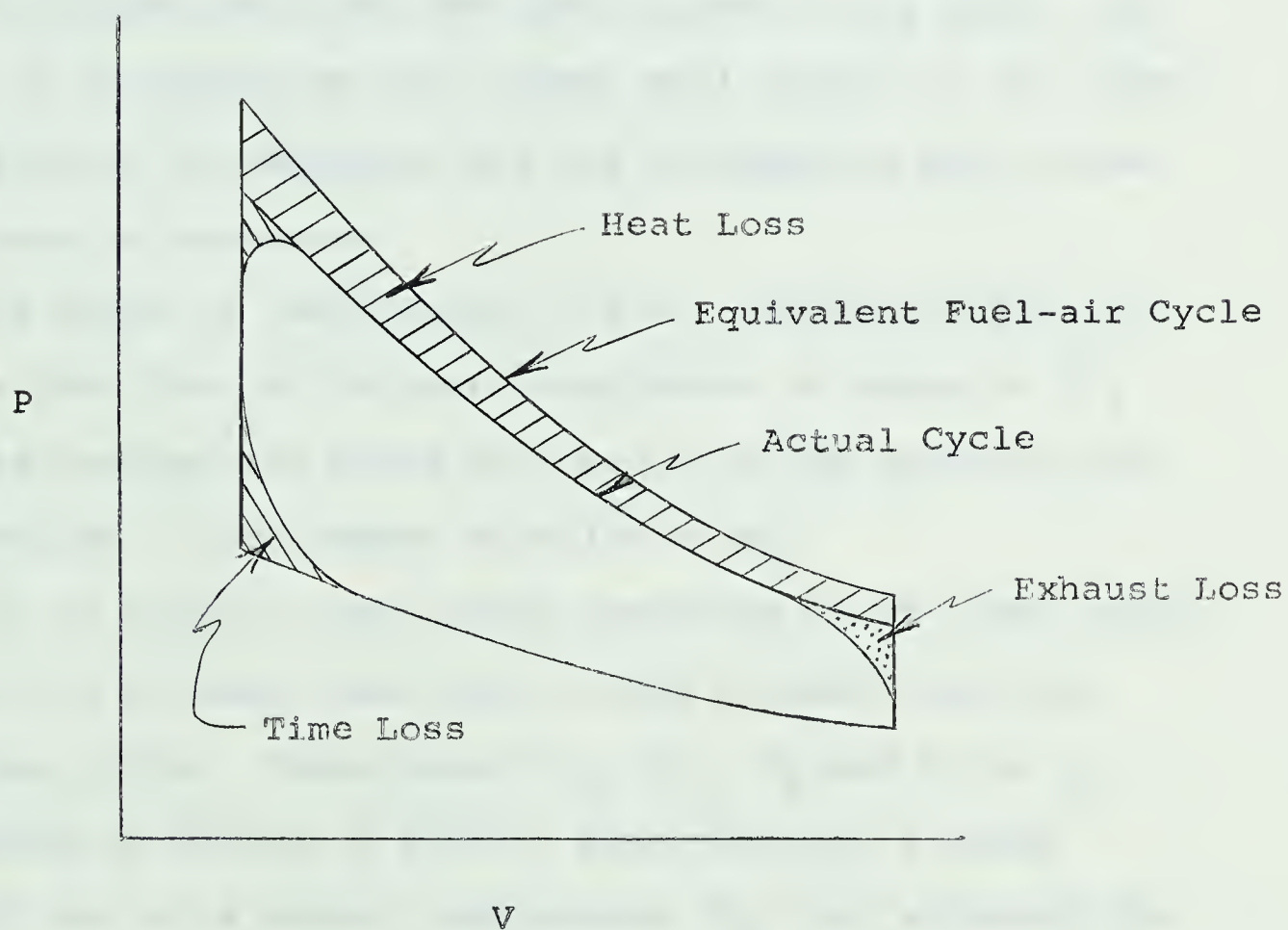


FIG. 2.2 ACTUAL FUEL-AIR CYCLE LOSSES





correct amount of air for complete combustion i.e. stoichiometric air-fuel ratio, is:



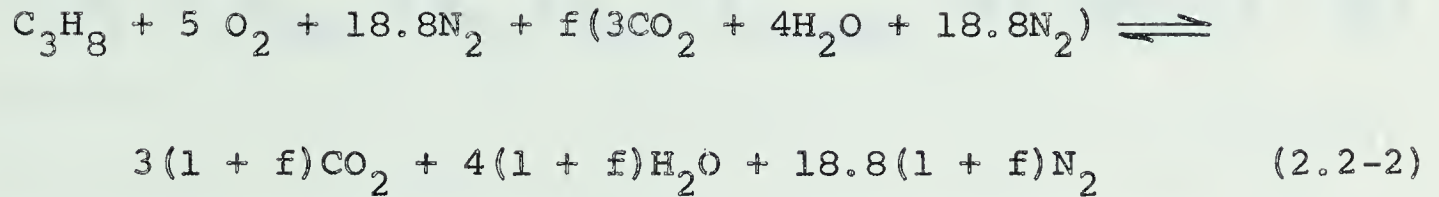
(assuming air 21% oxygen and 79% nitrogen by volume, where the % nitrogen includes the inert gases in the air). If there is an excess of air, oxygen will appear on the right hand side of the equation and the nitrogen on both sides will also be increased.

If there is insufficient air for complete combustion i.e. a rich fuel-air mixture the number of moles of  $\text{CO}_2$  will be reduced and there will be CO in the products and a reduction in the number of moles of  $\text{N}_2$ .

In an engine, even though operating on an ideal cycle, there will be some gases left in the cylinder from the previous cycle. These gases  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{N}_2$  and CO or  $\text{O}_2$ , depending on whether a rich or lean mixture is being burned, are at a higher temperature ( $T_5$ ) and although the volume is small (approximately 3% of  $V_5$ ) there is an appreciable increase in energy and temperature of the incoming mixture when mixed with the residual gases.

Assuming 100% air and "f" as the fraction of residual gases remaining in the cylinder the reaction equation 2.2-1 now becomes:





The temperature of the incoming fuel-air mixture may be measured and thus the enthalpy obtained. However, the temperature of the residual gases and "f" have to be estimated and later confirmed, i.e. a trial solution.

The internal energy at  $T_1$  may be expressed as:

$$U_1 = H_{\text{charge}} + U_{\text{Res. gas}} - \frac{P_1(V_1 - V_o)}{J}$$

but  $PV = MRT \quad \therefore \quad P_1 = \frac{MRT_1}{V_1}$

and  $V_o = V_2$

$$\therefore \frac{P_1(V_1 - V_o)}{J} = \frac{M(1545)}{778} \frac{T_1}{V_1} (V_1 - V_o)$$

$$= M(1.986)T_1 \left(1 - \frac{V_o}{V_1}\right)$$

$$= M(1.986)T_1 \left(1 - \frac{1}{\text{CR}}\right)$$

where CR is the compression ratio.



$$\therefore U_1 = H_{\text{fuel}} + H_{\text{O}_2} + H_{\text{N}_2} + U_{\text{res.gas}} - M(1.986)T_1\left(1 - \frac{1}{\text{CR}}\right)$$

(2.2-3)

At an assumed temperature  $T_1$ ,  $U_1$  can thus be obtained. Then considering the entire mixture at  $T_1$ , the sum of the internal energies of the gases can be obtained from:

$$U_1 = U_{\text{fuel}} + U_{\text{O}_2} + U_{\text{N}_2} + U_{\text{CO}_2} + U_{\text{H}_2\text{O}}$$

This process is repeated at various  $T_1$ 's until both calculated  $U_1$ 's are of the same value. The value of  $T$  thus obtained is taken as  $T_1$ .

Isentropic compression from  $T_1$  to  $T_2$  gives a means of obtaining  $T_2$ .

$$S_2 - S_1 = 0 = \sum MC_v \ln \frac{T_2}{T_1} + \sum MR \ln \frac{V_2}{V_1}$$

i.e.  $\sum MC_v \ln \frac{T_2}{T_1} = - \sum MR \ln \frac{V_2}{V_1} = \sum MR \ln \frac{V_1}{V_2} = \sum MR \ln \text{CR}$

Various values of  $T_2$  are assumed until

$$\sum MC_v \ln \frac{T_2}{T_1} = \left( \sum M \right) R \ln \text{CR} \quad (2.2-4)$$

The energy at  $T_2$  is then calculated from

$$U_2 = U_{\text{C}_3\text{H}_8} + U_{\text{O}_2} + U_{\text{N}_2} + U_{\text{CO}_2} + U_{\text{H}_2\text{O}}$$



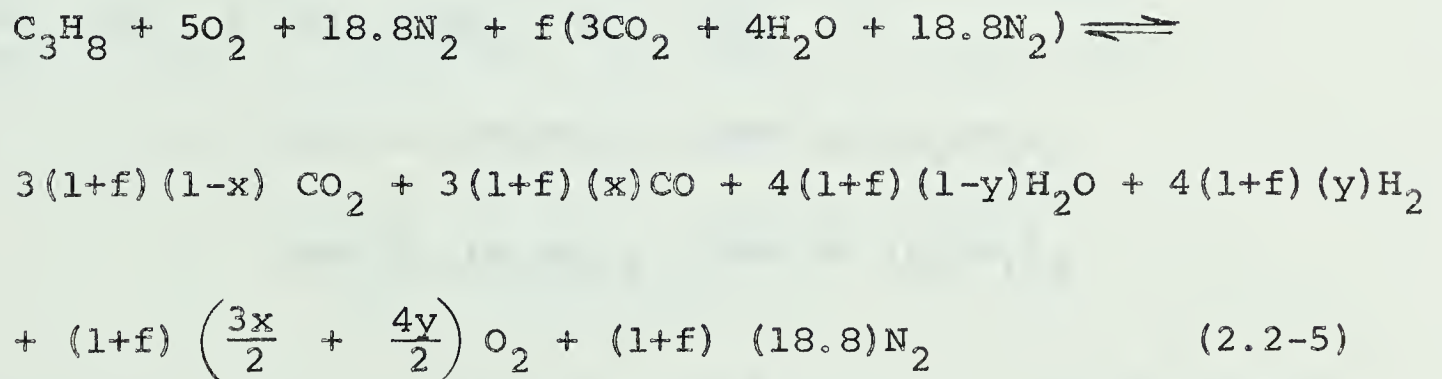


U and S are calculated using Cp and Cv as a function of temperature [11] or from the tables based on Cp and Cv as functions of temperature [12], (Table datum is 520°R).

The process 2-3 of Fig. 2.1 represents the combustion of the fuel at constant volume. In the ideal case this process is assumed to be adiabatic and the gas mixture is in equilibrium when state 3 is reached.

The mixture at the high temperature of  $T_3$  will contain unburned CO and  $H_2$  i.e. the  $CO_2$  and  $H_2O$  dissociates into CO and  $O_2$  and  $H_2$  and  $O_2$ , respectively.

If x and y represent the degrees of dissociation of  $CO_2$  and  $H_2O$ , respectively, the reaction equation, 2.2-2 can be written as:



The criteria for chemical equilibrium is that the Gibbs function (Gibbs free energy) for the system must be a minimum. The Gibbs function is defined as:

$$G = H - TS$$

By differentiating and substituting it can be shown that



$$dG = VdP - SdT$$

At the final approach to equilibrium the process may be considered isothermal, i.e.  $dT = 0$ .

$$\therefore dG = VdP$$

Assuming a perfect gas relationship:  $V = \frac{RT}{P}$

$$\therefore dG = RT \frac{dP}{P}$$

Integrating this equation gives:

$$G_2 - G_1 = \Delta G = RT \ln (P_2/P_1).$$

For the reaction  $aA + bB \rightleftharpoons cC + dD$

$$\begin{aligned} \Delta G_2 - \Delta G_1 &= \Delta G_C + \Delta G_D - G_A - \Delta G_B \\ &= cRT \ln (P_2/P_1)_C + dRT \ln (P_2/P_1)_D \\ &\quad - aRT \ln (P_2/P_1)_A - bRT \ln (P_2/P_1)_B \\ &= RT \ln \frac{(P_{2C})^c (P_{2D})^d}{(P_{2A})^a (P_{2B})^b} - RT \ln \frac{(P_{1C})^c (P_{1D})^d}{(P_{1A})^a (P_{1B})^b} \end{aligned}$$

Arbitrary values may be assigned so that the last term has a value of zero.

i.e.  $P_{1C} = P_{1D} = P_{1A} = P_{1B} = 1 \text{ atmosphere.}$





$$\therefore \Delta G_2' - \Delta G_1' = RT \ln \frac{(P_{2C})^c (P_{2D})^d}{(P_{2A})^a (P_{2B})^b}$$

Considering point 2 as the condition at equilibrium where there is no change in free energy,  $\Delta G_2'$  becomes zero and  $\Delta G_1'$  becomes  $\Delta G^0$

$$\therefore -\Delta G^0 = RT \ln \frac{(P_C)^c (P_D)^d}{(P_A)^a (P_B)^b}$$

or 
$$e^{-\frac{\Delta G^0}{RT}} = \frac{(P_C)^c (P_D)^d}{(P_A)^a (P_B)^b} = K_p$$

where  $K_p$  represents the pressure equilibrium constant. Since the partial pressures of a mixture of gases may be assumed proportional to the mole fractions

$$K_p = \frac{(C)^c (D)^d}{(A)^a (B)^b} \quad (2.2-6)$$

$K_p$  is a function of temperature and values of  $K_p$  for various gases are tabulated [13]. Since the deviation of the actual gas from the ideal gas is slight, the compressibility correction factor  $Z$  may be taken as 1 in the range of temperatures and pressures encountered in combustion.

$$\therefore K = K_p$$



Considering the dissociation of  $2\text{CO}_2$  into  $2\text{CO}$  and

$$K_{\text{CO}_2} = \frac{[\text{CO}]^2 [\text{O}_2]}{[\text{CO}_2]^2} \quad (2.2-7)$$

Substituting for the values of the number of moles, from equation 2.2-5, equation 2.2-7 becomes:

$$K_{\text{CO}_2} = \frac{\left[ \frac{3(1+f)(x)P_3}{M_3} \right]^2 \left[ \frac{3(1+f)x + 4(1+f)y}{2M_3} \right] P_3}{\left[ \frac{3(1+f)(1-x)}{M_3} P_3 \right]^2}$$

$$= \left[ \frac{x}{1-x} \right]^2 \left[ \frac{3}{2} (1+f)x + \frac{4}{2} (1+f)y \right] \frac{P_3}{M_3}$$

but  $\frac{P_3}{M_3} = \frac{RT_3}{V_3}$  where  $R = \frac{P_2 V_2}{M_2 T_2}$  and  $V_2 = V_3$

$$\therefore K_{\text{CO}_2} = \left[ \frac{x}{1-x} \right]^2 \left[ \frac{3}{2} (1+f)x + \frac{4}{2} (1+f)y \right] \frac{P_2 T_3}{M_2 T_2} \quad (2.2-8)$$

The equilibrium constant for the dissociation of  $2\text{H}_2\text{O}$  may be expressed in the same manner.

For reasons to be explained later it is advantageous



to determine the water-gas equilibrium constant  $K_{WG}$  rather than  $K_{H_2O}$ . Considering the two equations:



Subtraction gives



or



$$\therefore K_{WG} = \frac{\left(P'_{CO}\right) \left(P'_{H_2O}\right)}{\left(P'_{CO_2}\right) \left(P'_{H_2}\right)} \quad (2.2-9)$$

In terms of  $x$  and  $y$  and mole fractions this equation becomes

$$K_{WG} = \frac{x(1-y)}{(1-x)y} \quad (2.2-10)$$

Values of  $K_{WG}$  at various temperatures are also tabulated [13].

Theoretically, the  $H_2$ ,  $O_2$  and  $N_2$  will dissociate into their respective atoms and small amounts of  $OH$ ,  $NO$ ,  $NH_3$  and  $CH_4$  may form, but at high pressures as found in the Otto cycle, this dissociation is very slight and is neglected in this analysis.

$T_3$  may be obtained by using the first Law of Thermodynamics,





expressed as:

$$U_2 + CE_{\text{fuel}} = U_3$$

$U_2$  and the CE of the fuel are known. The CE is obtained from  $CE + U_{O_2} + U_{\text{fuel}} = U_{CO_2} + U_{H_2} + \text{Heating Value of fuel}$ .

$$\text{Heating Value of } C_3H_8 = 878,749 \text{ BTU/mole } [14].$$

$$\begin{aligned} U_3 &= U_{CO_2} + U_{CO} + U_{H_2O} + U_{H_2} + U_{O_2} + U_{N_2} \\ &= 3(1+f)(1-x) u_{CO_2} + 3(1+f)x u_{CO} + \\ &\quad 4(1+f)y u_{H_2} + (1+f)\left(\frac{3x}{2} + \frac{4y}{2}\right) u_{O_2} + 18.8(1+f)u_{N_2} \end{aligned} \quad (2.2-11)$$

$T_3$ ,  $x$  and  $y$  are yet unknown, therefore, this equation cannot be solved.

Considering equations 2.2-8, 2.2-10 and 2.2-11 there are three equations with five unknowns  $T_3$ ,  $x$ ,  $y$  and  $K_{WG}$  and  $K_{CO_2}$ , since the "u's" of equation 2.2-11 are all known functions of temperature. A trial solution is involved to obtain  $T_3$ .  $T_3$  is assumed, and the internal energies of the various gases in equation 2.2-11 are obtained by using the equations  $u = \int C_p dT$  where  $C_p$  is a function of temperature [11,12]. The  $x$ ,  $y$  and numerical terms are added algebraically resulting in an equation of the form,



$$U_2 + CE_{C_3H_8} - \sum N_{\text{terms}} = x \sum x_{\text{terms}} + y \sum y_{\text{terms}}$$

Therefore  $y$  may be obtained in terms of  $x$

$$\text{i.e.} \quad y = \frac{\text{Number} - x \sum x_{\text{terms}}}{\sum y_{\text{terms}}} \quad (2.2-12)$$

From equation 2.2-10,  $y$  can also be obtained in terms of  $x$ , as  $K_{WG}$  can now be obtained for the assumed value of  $T_3$ .

$$y = \frac{x}{K_{WG} - x(K_{WG} - 1)} \quad (2.2-13)$$

Equating equations 2.2-12 and 2.2-13 eliminates  $y$  and results in a quadratic equation in terms of  $x$  from which a value of  $x$  may be obtained.  $y$  may then be calculated from either equation 2.2-12 or equation 2.2-13. Using these values of  $x$  and  $y$  in equation 2.2-8 a value is obtained for  $K_{CO_2}$ . This procedure is repeated at various  $T_3$ 's until  $K_{CO_2}$  calculated is approximately equal to  $K_{CO_2}$  as tabulated [13]. When various  $T_3$ 's are obtained, the correct  $T_3$ ,  $x$  and  $y$  may be obtained by linear interpolation or by graphical means, such that  $K_{CO_2}$  calculated equals  $K_{CO_2}$  from the tables.

Process 3-4 is assumed to be isentropic expansion, therefore  $S_3 = S_4$ . Knowing  $T_3$ ,  $x_3$  and  $y_3$  the entropy at 3 may be calculated by the equation:





$$s_3 = \sum \phi - \sum MR \ln pp. + \frac{M_{CO}^{CE} CO}{T_3} + \frac{M_{H_2}^{CE} H_2}{T_3} \quad (2.2-14)$$

where  $\phi$  is  $M \int \frac{C_p dt}{T}$  and  $pp$  is the partial pressure of the constituent gas.

The determination of  $T_4$  again involves a trial solution since the degrees of dissociation of the  $CO_2$  and  $H_2O$  cannot be determined until after  $T_4$  is obtained. Assuming a value of  $T_4$ ,  $K_{CO_2}$  and  $K_{WG}$  may be obtained from the tables. Using equation 2.2-13,  $y$  may be obtained in terms of  $x$ . Substituting in equation 2.2-8 results in

$$K_{CO_2} = \left( \frac{x}{1-x} \right)^2 \left[ \frac{3}{2} (1+f)x + \frac{\frac{4}{2} (1+f)x}{K_{WG} - (K_{WG} - 1)x} \right] \frac{P_4}{M_4}$$

$$\text{but } \frac{P_4}{M_4} = \frac{RT_4}{V_4} = \frac{RT_4}{V_1} = \frac{P_1 V_1}{M_1 T_1} \cdot \frac{T_4}{V_1} = \frac{T_4 (1.)}{M_1 T_1}$$

since  $P_1 = 1. \text{ atm.}$

therefore

$$K_{CO_2} = \left( \frac{x}{1-x} \right)^2 \left[ \frac{3}{2} (1+f)x + \frac{\frac{4}{2} (1+f)x}{K_{WG} - (K_{WG} - 1)x} \right] \frac{T_4}{M_1 T_1} \quad (2.2-15)$$

Various values of  $x$  are assumed and substituted until  $K_{CO_2}$  as calculated equals the value of  $K_{CO_2}$  obtained from



the tables.

Using the assumed value of  $T_4$ ,  $x_4$  and  $y_4$  as obtained, the entropy at  $T_4$  may be calculated by the equation

$$s_4 = \sum \phi - \sum MR \ln pp + \frac{M_{CO} CE_{CO}}{T_4} + \frac{M_{H_2} CE_{H_2}}{T_4}$$

If  $s_4$  exceeds  $s_3$ ,  $T_3$  is assumed lower, and vice versa.

The above procedure is repeated until  $s_3 = s_4$ , thus giving the temperature  $T_4$ .

At 4, the end of the expansion process, the exhaust valve opens and the combustion products escape from the cylinder and the pressure decreases to atmospheric pressure. The gases in the cylinder expand isentropically to atmospheric pressure. Some of these gases remain in the clearance space in the cylinder. Considering this as condition 5 it is possible to calculate  $V_5$ , and knowing  $V_2$  check on the assumed value of "f" and also the assumed value of  $T_5$ . Since  $T_5$  is in the order of 2200°R it is reasonable to assume the amount of dissociation of  $CO_2$  and  $H_2O$  is negligible.

For an assumed  $T_5$  the entropy of 5 may be calculated using

$$s_5 = \sum \phi_5 - \sum MR \ln pp.$$

Various  $T_5$ 's are assumed until a value is obtained which



results in  $S_5 = S_3$ .

The fraction of residual gas,  $f = \frac{V_2}{V_5}$ , may now be obtained

$$V_2 = \frac{V_1}{CR} = \frac{M_1 RT_1}{14.7(144)CR}$$

and 
$$V_5 = \frac{M_5 RT_5}{14.7(144)}$$

therefore 
$$f = \frac{V_2}{V_5} = \frac{T_1 (M_1)}{CR (T_5) M_5} \quad (2.2-16)$$

If  $T_5$  and "f" differ greatly from the initially assumed values of "f" and  $T_5$  the entire calculations must be repeated until there are negligible changes in "f" and  $T_5$ .

The thermal efficiency is defined as

$$\begin{aligned} \eta &= \frac{\text{Net Work}}{\text{Heat Added}} \\ &= \frac{(U_3 - U_4) - (U_2 - U_1)}{\text{Heat Value of Fuel}} \end{aligned} \quad (2.2-17)$$

The heat value of propane is taken as the lower heat value of 19929 BTU/lb [14]. Knowing the temperatures  $T_1$ ,  $T_2$ ,  $T_3$  and  $T_4$  the internal energies may be calculated and the thermal efficiencies obtained by equation 2.2-17.

The mean effective pressure may be obtained from

$$\text{m.e.p.} = \frac{\text{net work}}{\text{displacement}}$$





$$\text{therefore m.e.p.} = \frac{(U_3 - U_4) - (U_2 - U_1)}{(V_1 - V_2) 144} \quad (2.2-16)$$

A sample calculation is given in Appendix A.

A computer programme in Fortran IV language was written to carry out the above calculations for various percentages of air, compression ratios, and various fuels. The computations were done on the IBM 7040-1401 system in the Department of Computing Science, University of Alberta. Appendix B shows this program. The results are plotted in Chapter IV. Iterations were continued until there was less than a  $1^\circ$  temperature variation in any particular assumed temperature or  $\frac{1}{2}\%$  variation in any other assumed value.

Convergence is illustrated by means of the table which follows. These results are at a compression ratio of 10. Results at other compression ratios showed similar effects.

Percent air	Thermal Efficiency		
	20% air Intervals		10% air Intervals
		1% variation	$\frac{1}{2}\%$ variation
100	36.8	36.9	36.9
110		39.5	39.5
120	43.7	41.8	41.8
130		43.6	43.6
140	58.3	44.8	44.8
150		45.0	45.0
160	46.6	46.6	46.6
170		46.2	46.2
180	46.5	46.9	46.9
190		47.7	47.7
200	46.2	47.9	47.9



## CHAPTER III

### EXPERIMENTAL WORK

#### 3.1 EQUIPMENT

The engine used in conducting these tests was an "ASTM-CFR-48 Engine" located in the Mechanical Engineering Laboratory of the University of Alberta. The engine is connected to a series wound D.C. motor capable of starting the engine and absorbing the power developed by it (dynamometer). The engine has a bore of 3.25 in., stroke of 4.50 in., variable spark adjustment and a variable, from 4 to 10, compression ratio. The standard CFR engine cooling system, evaporative cooling, was used to maintain the coolant temperature at 208°F (See Fig. 3-1).

The air flow into the air inlet surge tank was measured by means of an orifice and inclined manometer.

Gaseous propane was introduced into the air stream, at the throat of the carburetor, to ensure adequate mixing. The propane flow was measured by means of a "Precision" Wet Test Gas Meter, manufactured by Precision Scientific Co., placed in the propane gas line after the pressure reducer and before the engine carburetor. The meter capacity was 0.250 cu. ft. per revolution of the sweep dial, with a maximum pressure of 8 in. of water.

The combustion chamber mean temperature was obtained





by a chromel-alumel thermocouple, placed in the top of the cylinder, at the "knock-meter connection". The thermocouple readings were obtained on a Leeds and Northrup Millivolt potentiometer.

The time of runs, for the combustion of 0.500 cu. ft. of gas, and the number of revolutions per run were obtained on the timing unit on the control panel (see Fig. 3-2).

Exhaust gas analyses were obtained by means of a Hays Gas Analyzer (Orsat), capable of determining the percent by volume, of  $\text{CO}_2$ ,  $\text{O}_2$  and  $\text{CO}$ .

### 3.2 EXPERIMENTAL METHODS

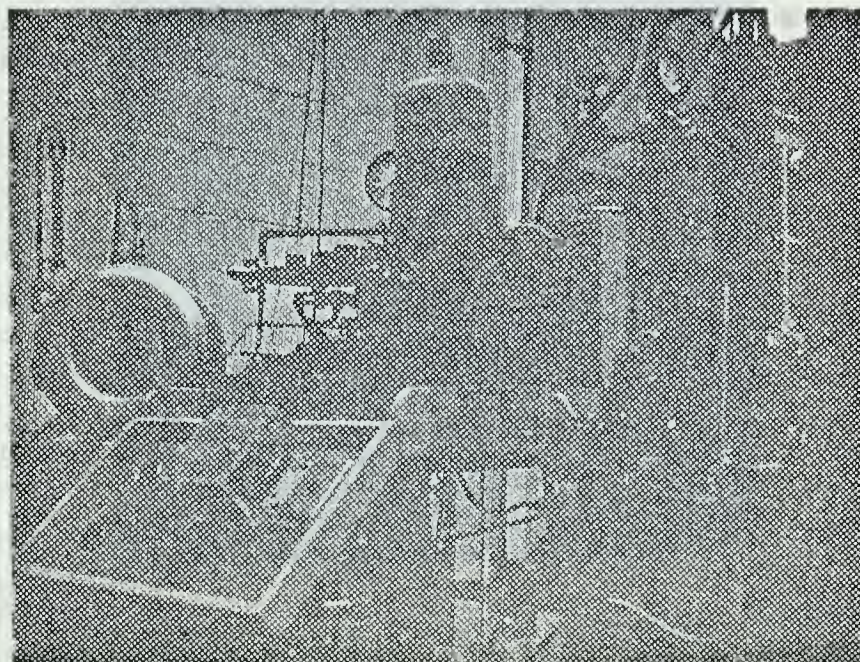
Initial tests were conducted with the engine as provided. Later tests were done with the engine exhaust valve replaced by a mild steel exhaust valve, manufactured locally, to determine the effects of oxidation, if any. No apparent changes occurred in the operation of the engine as a result of the changing of the exhaust valve. A photo of this valve showing the thermocouple wire is shown in Fig. 3.3.

#### 3.2-1 Test Procedure

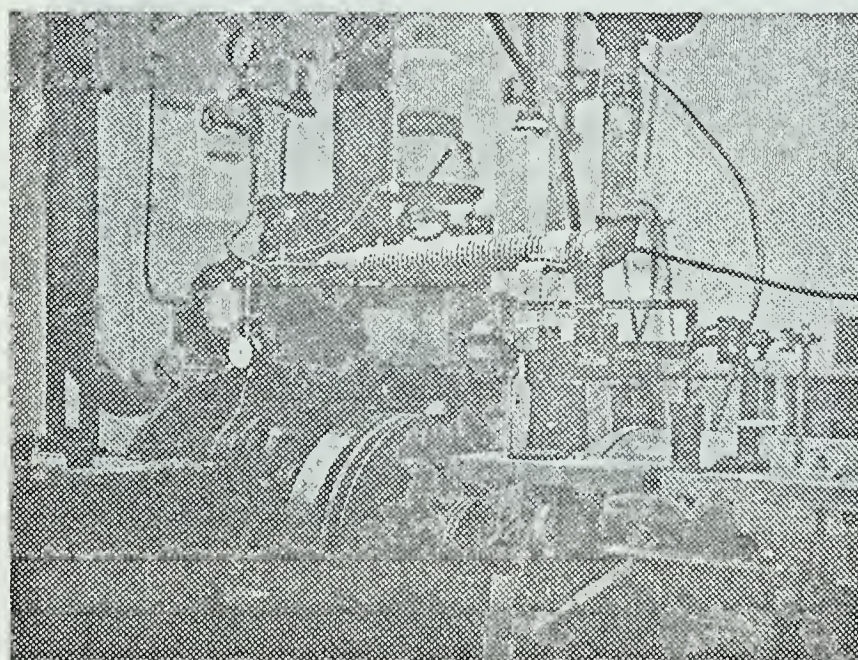
After preliminary testing, the engine oil was renewed and the micrometer gage, indicating the compression







Front View



Side View

FIG. 3-1 CFR-ENGINE AND TEST EQUIPMENT





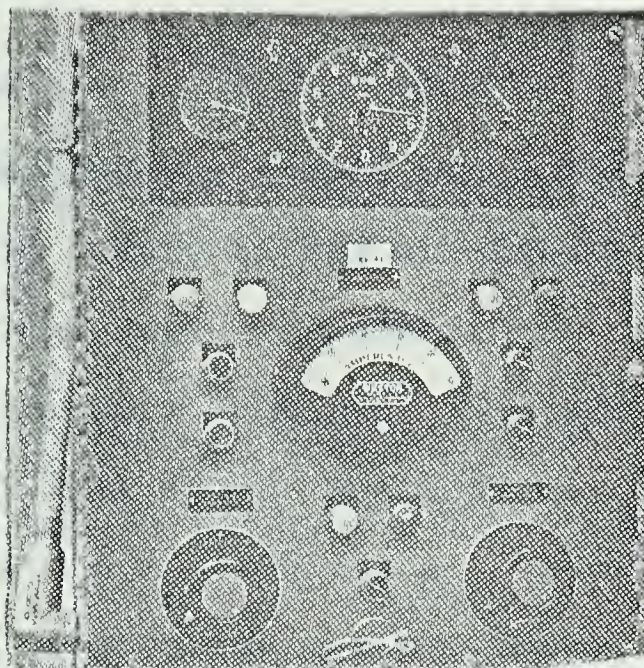


FIG. 3-2 CONTROL PANEL

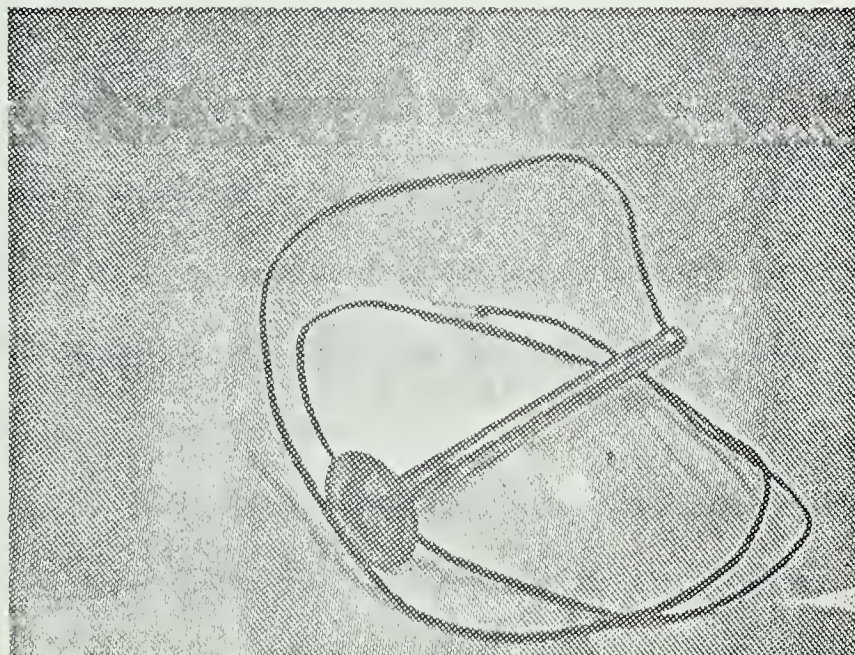


FIG. 3-3 WELD STEEL EXHAUST VALVE



ratio, was calibrated.

Prior to a test run the engine was operated for a considerable time to ensure it was at operating temperature. The compression ratio was set at the desired value and the gas pressure regulator adjusted to give the desired rate of fuel flow. The load was then adjusted to give the desired r.p.m. (600 for all tests). The spark was adjusted to give the maximum power output, indicated by the lifting of the load beam on the dynamometer. The speed was then re-adjusted and the spark re-adjusted again for maximum torque.

The throttle was run fully open and the fuel-air ratio varied by adjusting the gas flow rate only.

An exhaust gas sample was introduced into the gas analyzer at this time, and the timer initiated to record the time and number of engine revolutions for the burning of 0.500 cu. ft. of gas.

During the test run the exhaust gas was analyzed for  $\text{CO}_2$ ,  $\text{O}_2$  and CO and the following data recorded:

Test No.	Cooling Water Temperature
Oil Pressure	Barometric Pressure
Compression Ratio	Spark Angle
No. of Revolutions	Time
Fuel Temperature	Gas Meter Pressure





Air Temperature	Pressure of Air Manometer
Cylinder Temperature	% CO <sub>2</sub> by Volume
% O <sub>2</sub> by Volume	% CO by Volume
Dynamometer Load	

The above was repeated for a series of "runs" at the same compression ratio at different fuel flows. Immediately after a series of "runs" the engine was "motored" to determine the friction horsepower. A typical set of data is shown in Appendix C.

### 3.2-2 Calculations

1. In order to compensate for variations in ambient conditions a correction was made to refer all results affected by ambient conditions to the standard conditions adopted by S.A.E. i.e. atmospheric pressure of 29.00 in. Hg. and 85 °F. The correction factor is calculated by

the following formula  $CF = \frac{29.00}{\text{Bar. Pres.}} \sqrt{\frac{460 + T}{460 + 85}} \left[ \frac{15}{15} \right]$  (3.2-1)

### 2. Flow of Fuel

To determine the mass rate of flow of propane the following equations were used:

$$\text{Gas Pressure} = \text{ins. of H}_2\text{O} \times \frac{29.92}{33.899 \times 12} \quad (\text{ins. of Hg.})$$

(3.2-2)



Saturation Pressure of  $H_2O$ :

$$P_{sat} = \text{Sat. Pres.} + \frac{29.92}{14.696} \text{ (ins. Hg)} \quad (3.2-3)$$

where Sat. Pres. was obtained from Steam Tables [16].

Total Pressure ( $P_T$ ) = Bar. Pres. + Gas Pres. (ins. Hg)

$$\begin{aligned} \text{Volume (V)} &= V_o \frac{P_o}{P_{st}} \times \frac{T_{st}}{T_o}, \text{ from [7].} \\ &= V_o \frac{(P_t - P_{sat}) (460 + 60)}{29.92 (460 + \text{Gas Temp.})} \quad (\text{ft}^3) \quad (3.2-4) \end{aligned}$$

Using the specific volume of propane at  $60^\circ\text{F}$  and 1 atmosphere =  $8.503 \text{ ft}^3/\text{lb}$  [18] it is possible to calculate the weight of propane flowing per hour.

$$\begin{aligned} \text{Therefore, lbs. of } C_3H_8 \text{ per hour} &= \frac{V \times 60}{8.503 \times \text{time}} \quad (\text{lbs/hr}) \\ &\quad (3.2-5) \end{aligned}$$

### 3. Torque

The torque developed by the engine was obtained from the product of the load on the dynamometer scales and the moment arm of the dynamometer (10.52 ins).

$$\text{Torque} = \frac{10.52}{12} \times \text{load} \quad (\text{ft. lbs}) \quad (3.2-6)$$



## 4. Brake Horsepower

$$\text{BHP} = \frac{2\pi(\text{Torque})\text{r.p.m.}}{33,000} \quad (\text{H.P.}) \quad (3.2-7)$$

## 5. Friction Horsepower

$$\text{FHP} = 2\pi \left( \frac{10.52}{12} \right) \frac{(\text{Fr. Load})\text{r.p.m.}}{33,000} \quad (\text{H.P.}) \quad (3.2-8)$$

## 6. Indicated Horsepower

$$\text{IHP} = \text{BHP} + \text{FHP} \quad (\text{H.P.})$$

## 7. Corrected Indicated Horsepower

$$\text{CIHP} = \text{CF} \cdot \text{IHP} \quad (\text{H.P.})$$

## 8. Corrected Brake Horsepower

$$\text{CBHP} = \text{CIHP} - \text{FHP} \quad (\text{H.P.})$$

## 9. Thermal Efficiency

The thermal efficiency is the ratio of the work out to the heat added, expressed as a percent. Since this combustion process is at constant volume and the  $\text{H}_2\text{O}$  formed is in the gaseous state, the constant volume Lower Heating Value was used as the available heat.  $\text{L.H.V} = 19,929 \text{ BTU/lb.} \left[ 12 \right]$ .





$$\text{Indicated Thermal Efficiency } (\eta) = \frac{\text{CIHP}(2545)100}{\text{lb/hr.}(19,929)} \quad (\%)$$

$$\text{Brake Thermal Efficiency } (\eta_B) = \frac{\text{CBHP}(2545)100}{\text{lb/hr.}(19,929)} \quad (\%)$$

#### 10. Mechanical Efficiency

$$\text{Mech. eff} = \frac{\text{CBHP}}{\text{CIHP}} \times 100 \quad (\%)$$

#### 11. Fuel per Indicated Horsepower

$$\text{lb. fuel/Hr/CIHP} = \frac{\text{lb.}}{\text{CIHP-Hr.}}$$

#### 12. Fuel per Brake Horsepower

$$\text{lb. fuel/Hr/CBHP} = \frac{\text{lb.}}{\text{CBHP-Hr.}}$$

#### 13. Indicated Mean Effective Pressure

$$\text{IHP} = \frac{\text{PLAN}}{33,000} \quad (\text{by definition})$$

$$\text{Therefore} \quad P = \frac{\text{IHP}(33,000)}{\text{LAN}}$$

where

L = length of stroke

A = area of piston

N = number of power strokes per minute

$$= \frac{\text{r.p.m.}}{2}$$

In order to compensate for ambient conditions multiply



by the correction factor CF or rather than use IHP use CIHP.

$$\text{Therefore} \quad \text{IMEP} = \frac{(\text{CF}) \text{IHP}(33,000)}{\text{LAN}} \quad (\text{psi})$$

#### 14. Fuel to Air Ratio

$$\text{From the Ideal Gas Law, } PV = mR'T \quad V = \frac{mR'T}{P}$$

$$\rho = \frac{P}{mR'T} \quad \text{and } R' \text{ for air} = 53.34 \text{ ft-lbf/lbm. } ^\circ\text{R}$$

Air density ( $\rho$ )

$$\rho = \text{Bar. Pres.} \cdot \frac{14.696}{29.92} \cdot \frac{144}{53.34 \cdot \text{Air Temp.}} \quad (\text{lb/ft}^3)$$

$$\text{Head of air (h)} = \frac{\text{ins. on manometer (62.4)}}{\text{Air Dens. (12)}} \quad (\text{ft. of air})$$

$$\text{Velocity} = C \sqrt{2gh} = 0.062 \sqrt{64.4 h} \quad (\text{Ft/min})$$

where C is the orifice coefficient.

$$\text{Flow} = \frac{\text{Vel (Area) 60 (Density)}}{144} \cdot \text{CF} \quad (\text{lb/hr})$$

$$\text{Fuel Air Ratio} = \frac{\text{lb fuel per hour}}{\text{lb air per hour}}$$

A sample calculation is shown in Appendix D.

A computer program, using Fortran IV language, was written by the author to do the above calculations. Besides doing the above calculations the program was designed to



calculate the fuel-air ratio from the exhaust gas analysis, as a check on the exhaust gas analysis. This program also rearranges all results in descending order of fuel-air ratio before printing them, and it also plots some of the results against fuel-air ratio. This program will also calculate the similar results, if the fuel is gasoline. The program is shown in Appendix E.





## CHAPTER IV

### RESULTS

#### 4.1 EXPERIMENTAL RESULTS

A summary of the more pertinent results are tabulated in Table 4.1. A sample set of results, as calculated by the computer program is shown in Appendix F.

The results tabulated in Table 4.1 are shown plotted in Figs. 4.1 to 4.4 inclusive.

Fig. 4.1 shows the corrected (to Standard Atmospheric conditions) Indicated Mean Effective Pressure plotted against fuel-air ratio. As one would expect the m.e.p. decreases as the fuel-air ratio decreases. Increasing the compression ratio increases the m.e.p.

Fig. 4.2 is a plot of Indicated Thermal Efficiencies at various compression ratios plotted against fuel-air ratio. Increasing the compression ratio increases the thermal efficiency. As the fuel-air ratio decreases the thermal efficiency increases to a maximum value and then decreases.



TABLE 4.1

EXPERIMENTAL RESULTS

RUN	F/A Ratio (lb. fuel/lb. air)	CIHP (HP)	FU/CIHP (lb. fuel/HP)	FU/CBHP (lb. fuel/HP)	IMEP (psi)	I.Th.Eff (%)	B.Th.Eff (%)
<u>Test 5 CR = 7.81</u>							
1	0.0537	3.55	0.420	0.574	124.6	30.4	22.3
2	0.0448	3.34	0.371	0.515	119.2	34.4	24.8
3	0.0353	2.90	0.343	0.507	102.5	37.3	25.2
4	0.0342	2.70	0.359	0.553	94.9	35.6	23.1
5	0.0308	2.21	0.396	0.685	79.0	32.3	18.7
<u>Test 5 CR = 9.77</u>							
39	0.0577	3.65	0.459	0.635	128.7	27.9	20.1
40	0.0499	3.83	0.380	0.521	132.3	33.6	24.3
41	0.0416	3.60	0.336	0.466	127.8	38.1	27.4
42	0.0339	3.13	0.317	0.469	110.6	40.3	27.2
43	0.0267	2.30	0.344	0.620	80.4	37.1	20.6
<u>Test 5 CR = 9.82</u>							
48	0.0574	3.66	0.46	0.62	128.7	28.0	20.5
49	0.0501	3.80	0.38	0.51	133.2	33.5	24.8
50	0.0413	3.57	0.33	0.46	127.4	38.2	28.0
51	0.0320	2.96	0.32	0.47	104.8	40.4	27.1
52	0.0254	2.05	0.37	0.70	72.8	34.7	18.4









Fig. 4.3 shows the effect of fuel-air ratio on Brake Thermal Efficiency. Increasing the compression ratio has a pronounced effect on increasing the brake thermal efficiency.

Fig. 4.4 shows "Comparative Fuel Consumption Loops" showing the relationship of Indicated Thermal Efficiency and Indicated Mean Effective Pressure and the effect of compression ratio.

#### 4.2 THEORETICAL RESULTS

Fig. 4.5 shows a comparison of theoretical thermal efficiencies plotted against percent theoretical air for the results as obtained in this work with the earlier work of Goodenough and Baker [1], and results from Taylor [9] which he obtained by using the charts of Hottel, Williams, and Satterfield. The latter two sets of results are for gasoline as the fuel and are not primarily interested in very lean mixtures but range from lean to rich.

Figs. 4.6 and 4.7 show the effects of compression ratio and fuel-air ratio on the Theoretical Mean Effective Pressure and the Adiabatic Flame Temperature ( $T_3$ ), respectively.



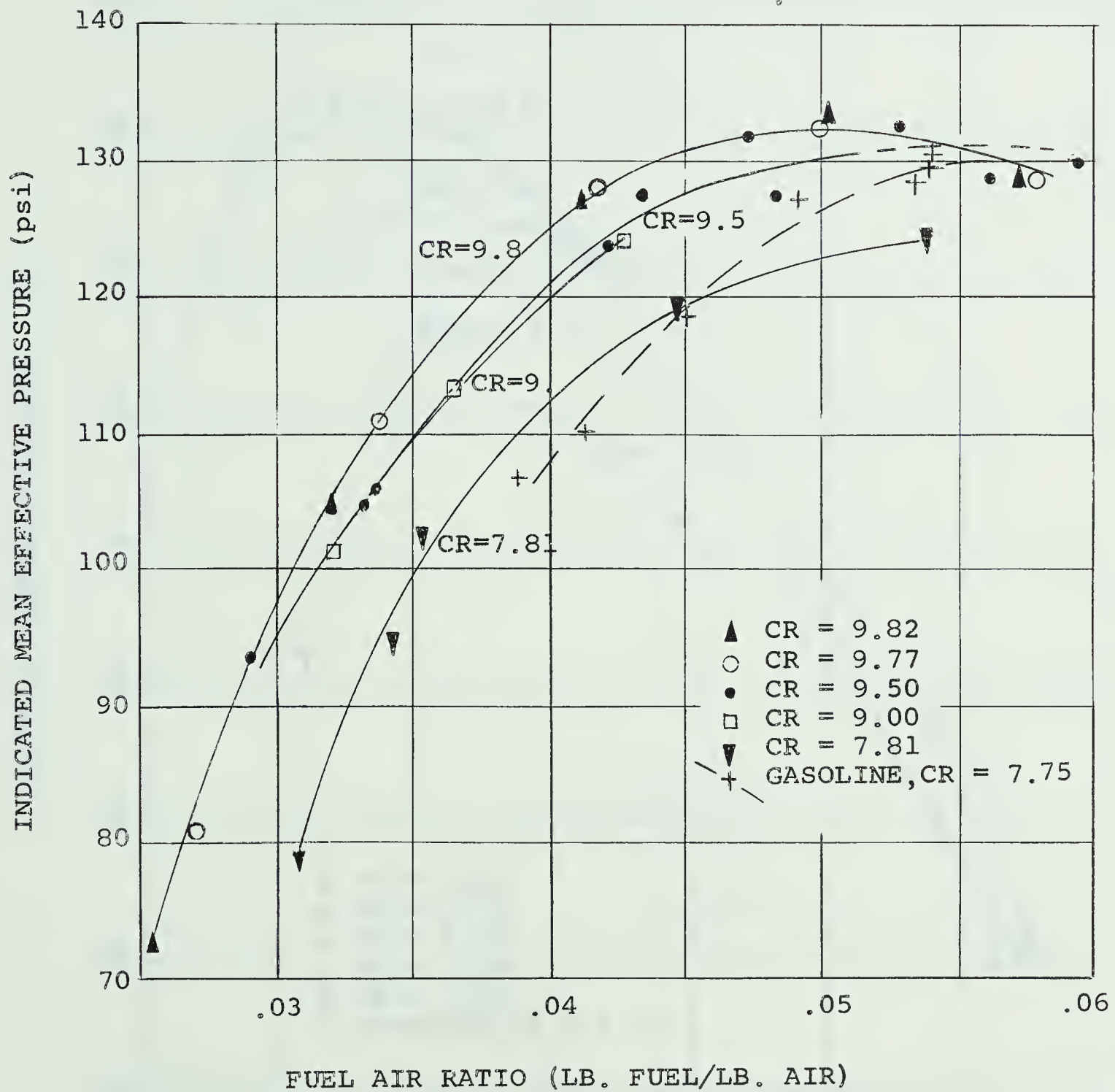


FIG. 4.1 INDICATED MEAN EFFECTIVE PRESSURE





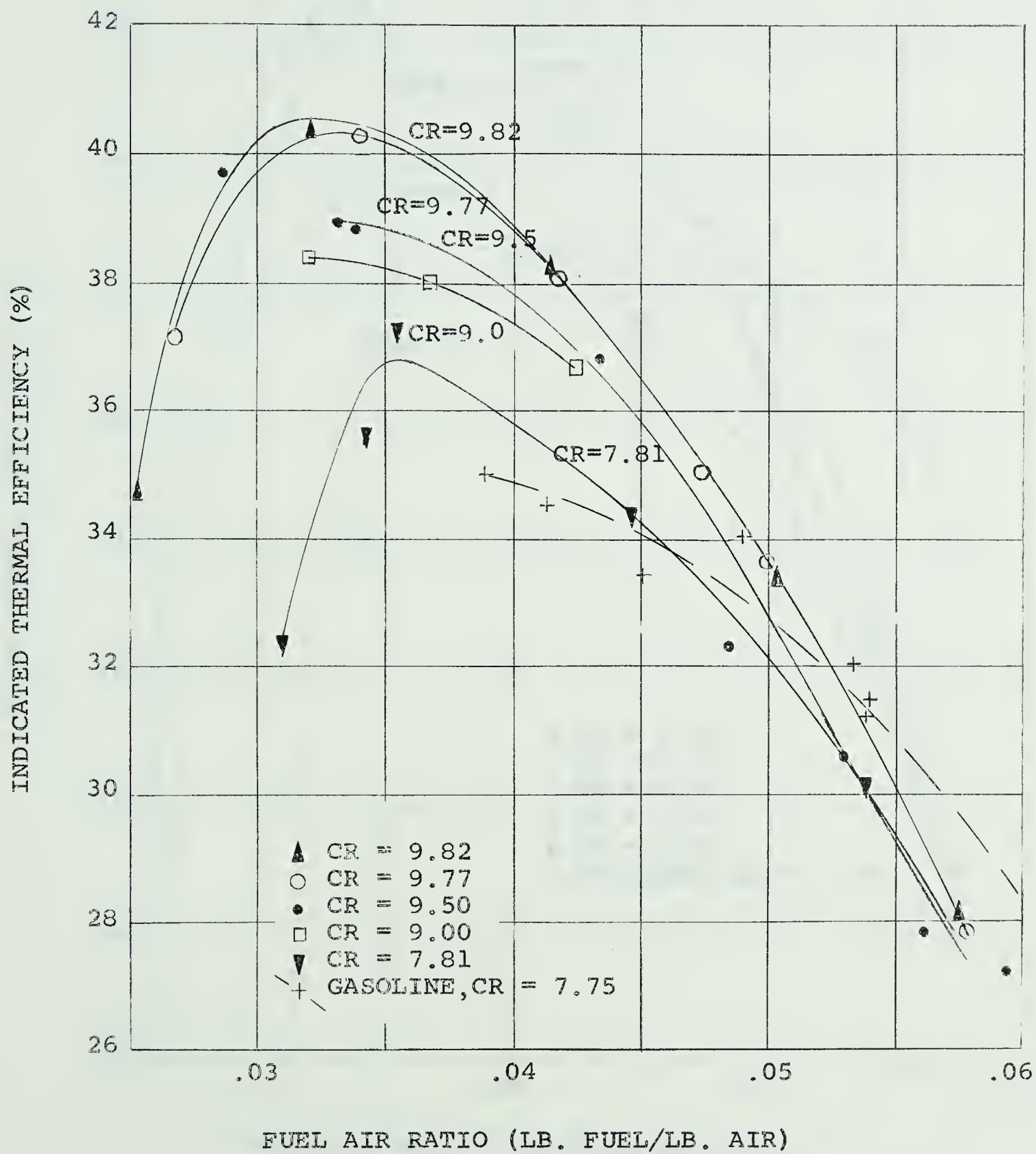


FIG. 4.2 INDICATED THERMAL EFFICIENCIES



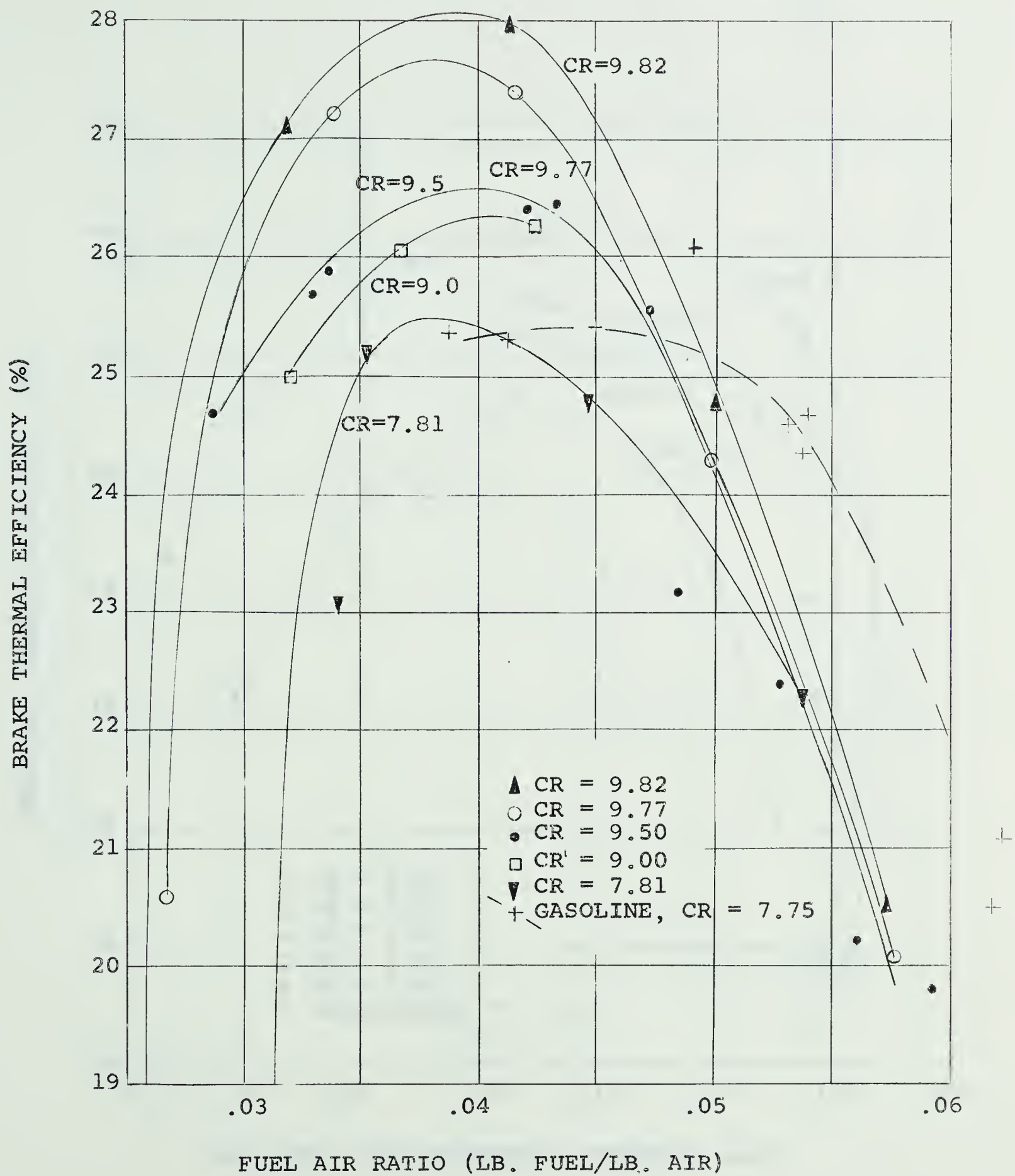


FIG. 4.3 BRAKE THERMAL EFFICIENCY





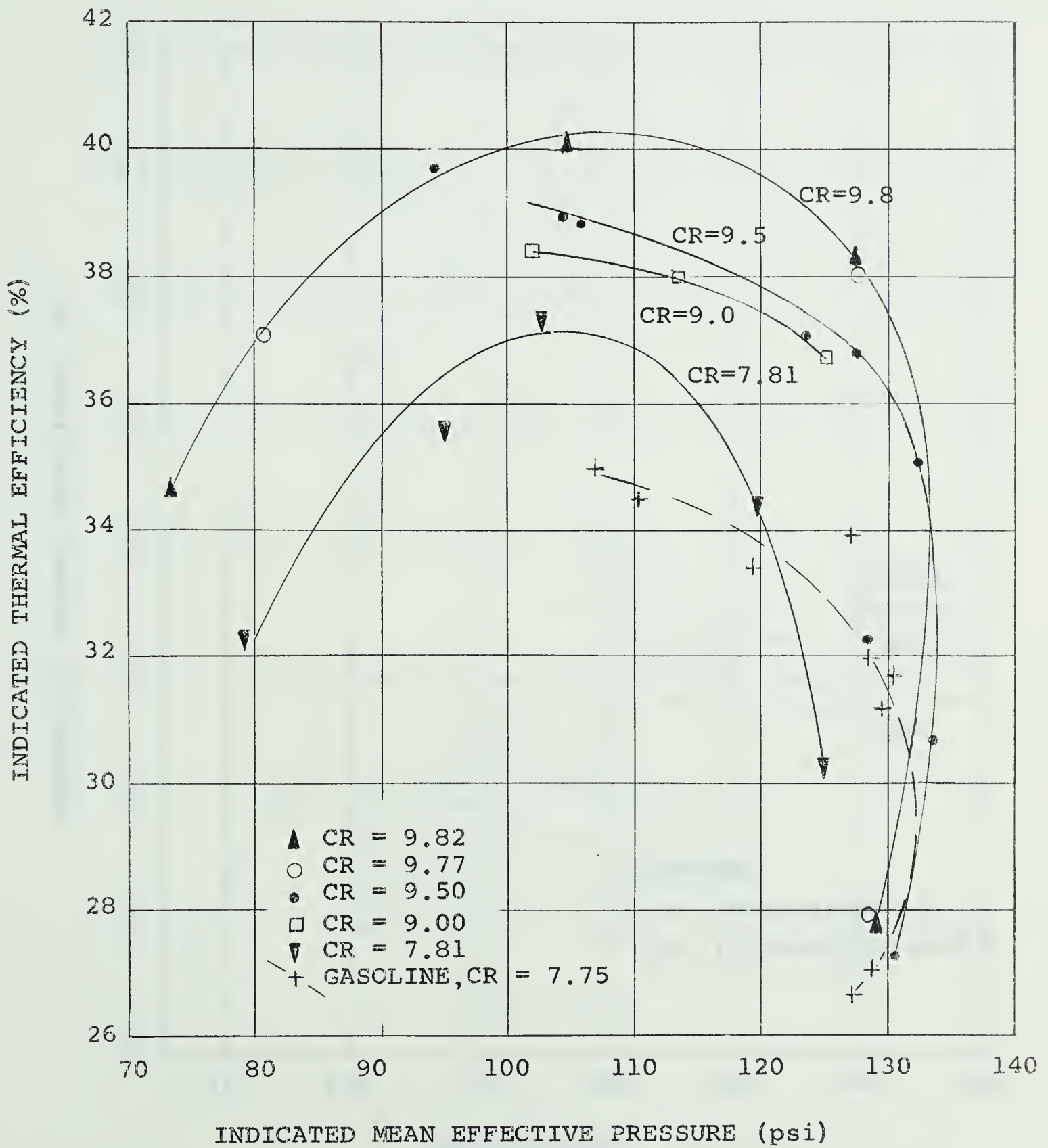


FIG. 4.4 "COMPARATIVE FUEL CONSUMPTION LOOPS"



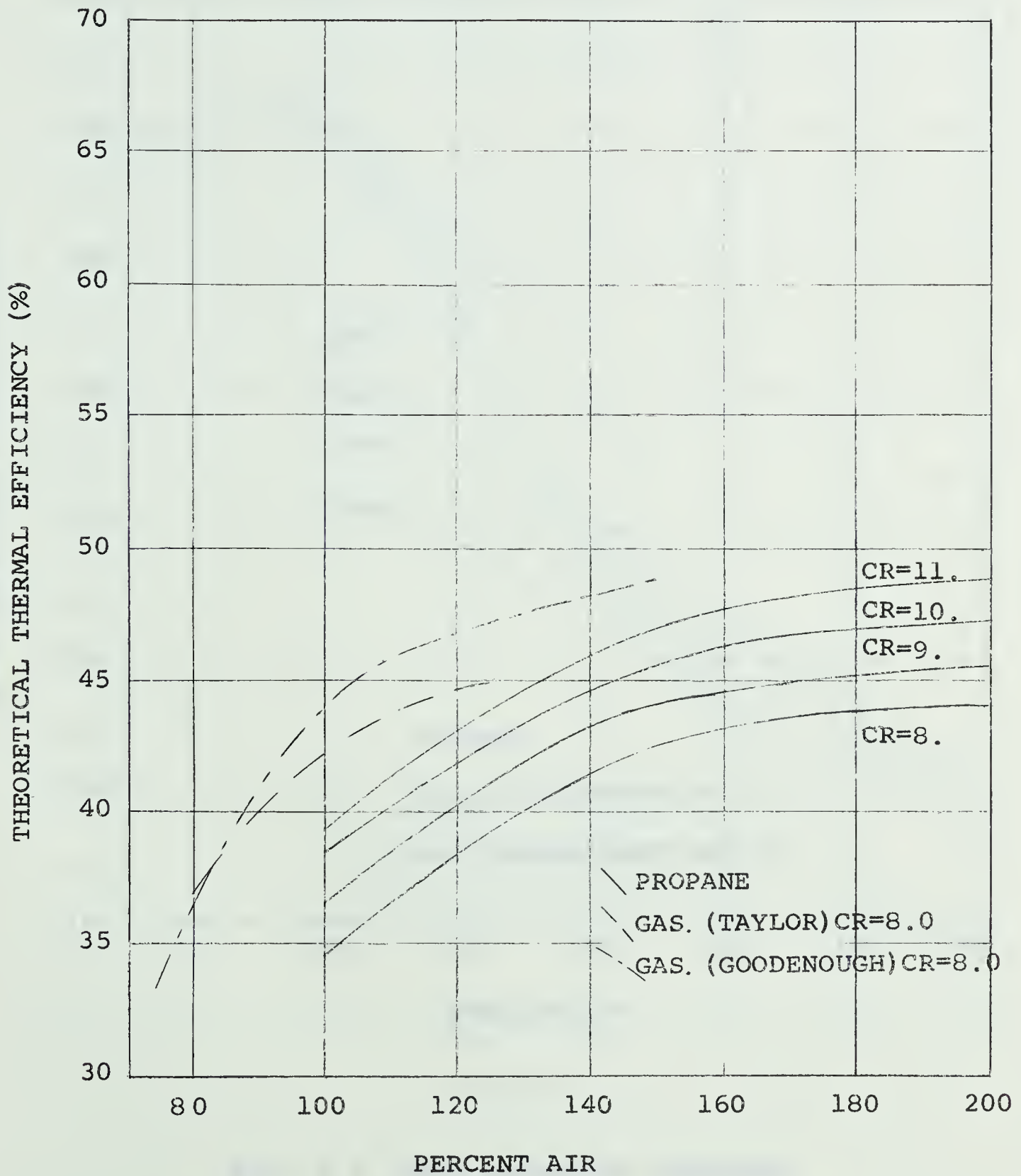


FIG. 4.5 THEORETICAL THERMAL EFFICIENCY



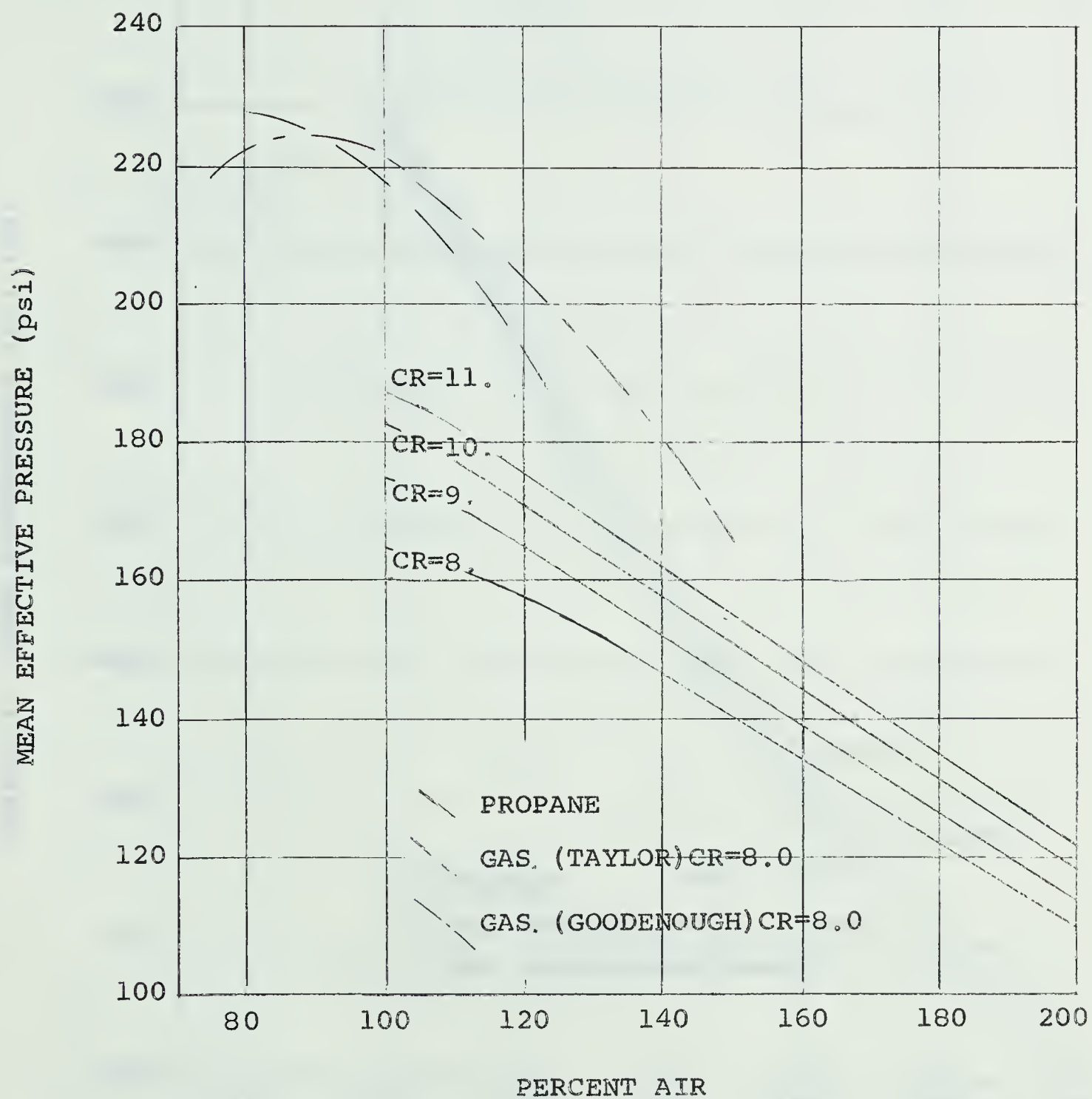


FIG. 4.6 MEAN EFFECTIVE PRESSURE





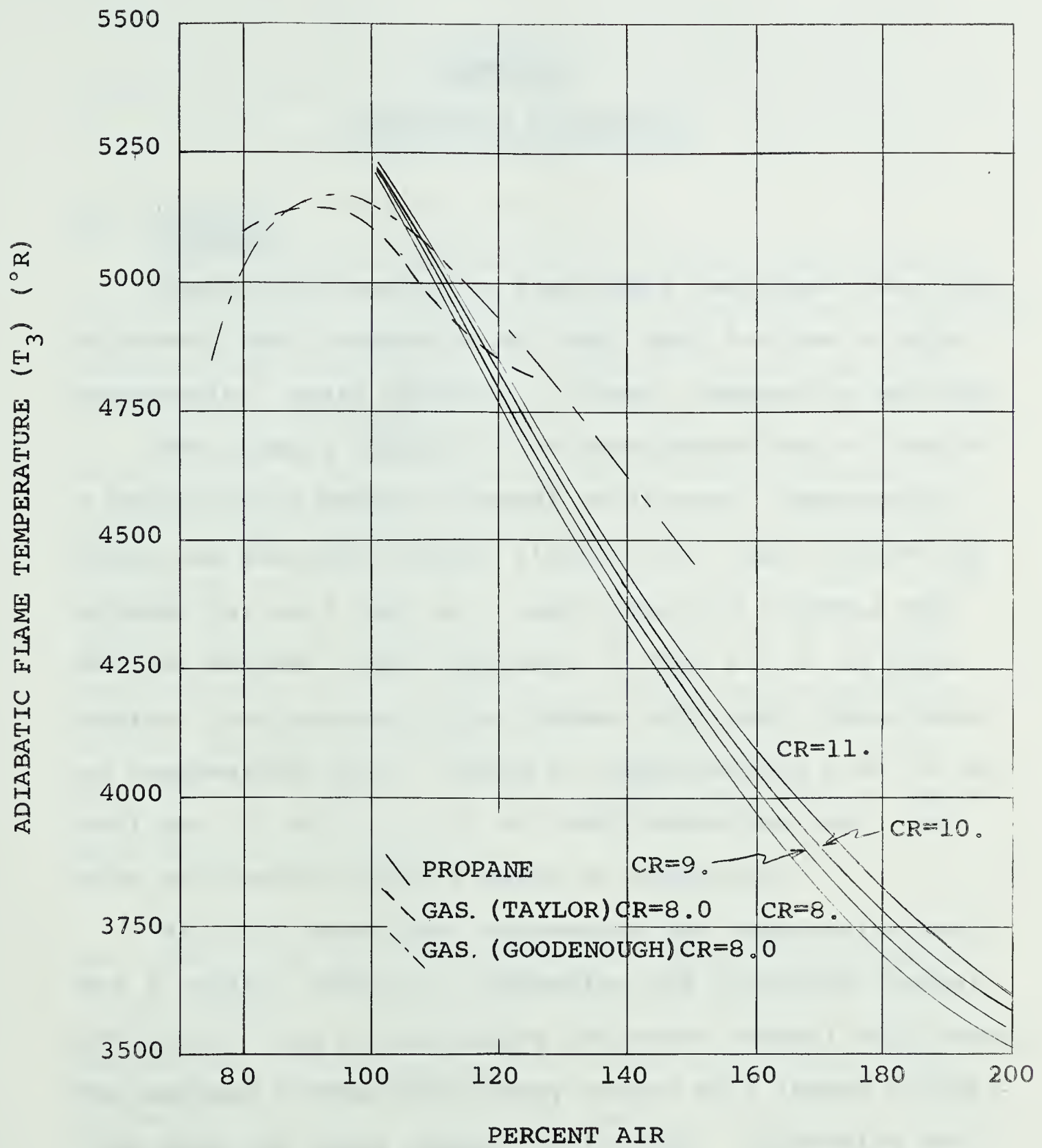


FIG. 4.7 ADIABATIC FLAME TEMPERATURE



## CHAPTER V

### DISCUSSION OF RESULTS

#### 5.1 GENERAL

These experiments, as previously mentioned, show conclusively that propane is an ideal fuel for use in high compression, spark ignition, internal combustion engines.

The primary object of the experiments was to obtain a relationship between thermal efficiency, compression ratio and fuel-air mixture strength for lean mixtures of propane gas as a fuel in a spark ignition internal combustion engine. With reference to Fig. 4.3 it is quite obvious that maximum brake thermal efficiency regardless of compression ratio, occurs at approximately 0.04 lb. of fuel per lb. of air, i.e. at 160% theoretical air, for this particular engine running at 600 r.p.m.

Fig. 4.2 shows that increasing the compression ratio has a smaller effect on increasing the indicated thermal efficiency than on increasing the brake thermal efficiency. The maximum thermal efficiency occurs at a leaner mixture than does the brake thermal efficiency. Increasing the compression ratio causes the maximum indicated thermal efficiency to occur at a leaner mixture due to the increase in the fuel reaction rate as a result of the increased pressure.





Fig. 4.4 indicates as one would expect that the maximum thermal efficiency does not occur at maximum mean effective pressure but at approximately 100 to 110 psi regardless of the compression ratio.

With reference to Fig. 4.4 it may be concluded that for this engine running at 600 r.p.m. the maximum indicated mean effective pressure of the engine when the fuel is a lean mixture of propane at a compression of 9 or 10 is the same as the m.e.p. when the fuel is gasoline at a compression ratio of 7.75 (The highest CR at which the engine will operate without knock). However, the thermal efficiency of the engine when the fuel is propane is greater than when the fuel is gasoline at the lower compression ratio. Lowering the compression ratio results in a reduction in both the thermal efficiency and the indicated mean effective pressure.

## 5.2 COMPARISON - EXPERIMENTAL AND THEORETICAL RESULTS

Although the air standard Otto cycle indicates that the thermal efficiency for air increases to 100 percent (equation 2.3) this is not the case with fuel-air mixtures even though the mixture may be made leaner, i.e. approaching 100% air. The efficiency reaches a maximum value and then decreases, prior to the leanest mixture on which the engine will continue to run smoothly. This may be



attributable to the fact that the engine must rely on the fuel, only, for its heat, which is not the case when using the ideal cycle for air. An optimum fuel-air ratio is reached beyond which, due to the great excess of air, the fuel does not ignite.

Although the thermal efficiencies and brake mean effective pressures obtained experimentally are lower than the theoretical results, due to losses previously mentioned in Chapter II, when the curves are compared they both have the same general trends and experimental results are approximately 70% of the theoretical results.

### 5.3 EXPERIMENTAL ERROR

Although as many variables as possible were controlled and a correction factor applied to relate all calculations affected by ambient conditions to a standard base, variations in ambient conditions did affect results. As an example, the rate of heat transfer from the engine and from the room into the intake manifold vary as the room temperature changes and these variations, which could not be determined, did have an effect on the operation of the engine.

Speed fluctuated during tests, even though the settings were unaltered. These fluctuations, at very lean mixtures were in the order of 5% and although they would





have a minimal effect on the averaged rates of fuel and air consumption they would have an effect on the torque. In an effort to compensate for this, all readings were taken in the same order for each test. It may also be due to these fluctuations that some of the exhaust gas analyses were incorrect.

#### 5.4 MISCELLANEOUS OBSERVATIONS

The engine operates smoothly on fuel-air ratios down to approximately 0.028 lb. propane/lb. air (230% air) at which point the engine begins to misfire due to incomplete combustion of the fuel.

The mean temperature of the combustion chamber is less than 1000 °F in the range tested, ranging from 900 ° at the higher fuel-air ratio down to approximately 500 ° at the very lean mixtures. The mean temperature is lower when using propane than when using gasoline as the fuel.

The mild steel exhaust valve functioned well during the 23 hrs. it was installed. There was no loss of compression due to corrosion and observation indicates no apparent corrosion of the valve. An attempt was made to measure the exhaust valve temperature by means of a thermocouple mounted flush in the face of the valve and the wires extending through a hole drilled axially along the valve. In order to avoid modification of the rocker





arm mechanism a radial hole was drilled at the top of the valve stem just below the rocker arm to bring out the thermocouple wires. This procedure did not work due to the fact the valve rotates and the thermocouple wire insulation frayed and shorted the wires.



## CHAPTER VI

### CONCLUSIONS AND RECOMMENDATIONS

#### 6.1 CONCLUSIONS

This thesis has described a theoretical and experimental investigation of the burning of lean mixtures of propane gas in a spark ignition internal combustion engine. It has been shown that lean mixtures of propane are satisfactory for the operation of spark ignition internal combustion engines.

Although the theoretical analysis indicates higher thermal efficiencies and higher mean effective pressures than obtained experimentally, both sets of results, in general, have the same trends. The reason that the results obtained from the theoretical analysis are higher than the results obtained experimentally may be attributed to the fact that the theoretical analysis is for an ideal fuel-air cycle i.e. the processes are assumed to be adiabatic with isentropic compression and expansion and the effects of pressure losses during the induction and exhaust processes are ignored. The mean effective pressures obtained experimentally are approximately 70% of the values obtained by the theoretical analysis. The theoretical thermal efficiency shows a continuous increase, reaching a maximum of 48.5% at a CR = 11 and 200% air (The limit of this calculation). The rate of increase decreases as the mixture becomes leaner. The indicated thermal





efficiency, obtained experimentally, initially shows an increase as the air is increased but it reaches a maximum value of 40.5% at  $CR = 9.8$  and then decreases quite rapidly. The fact that the thermal efficiency reaches a maximum and then decreases may be attributed to the effect of heat transfer from the combustion chamber. As the fuel air mixture becomes leaner a fuel-air ratio is reached where the amount of heat transfer becomes greater than the amount of heat available to do work on the piston thus causing a decrease in the thermal efficiency. Increasing the compression ratio causes an increase in both the thermal efficiency and the mean effective pressure in both the theoretical analysis and experimental analysis. Increasing the compression ratio also causes the maximum thermal efficiency, as obtained experimentally, to occur at a leaner mixture, due to the combustion process approaching a constant volume burning, in a shorter time interval, thus reducing the amount of heat transfer.

Maximum fuel economy, as indicated by the brake thermal efficiency, is obtained when the fuel-air ratio is at 0.04 lb. of propane per lb. of air (160% of theoretical air) at an engine speed of 600 r.p.m. The compression ratio has a negligible effect on the maximum brake thermal efficiency and maximum fuel economy.

Lean mixtures of propane and gasoline, both at the



highest compression ratio without knock, result in approximately the same maximum mean effective pressure, 132 psi. However, since propane is knock free at higher CR's the thermal efficiency of propane at a higher CR is greater than gasoline at the highest CR it may be used (7.75).

Lean mixtures of propane result in a lower engine operating temperature than when the engine is burning gasoline.

There is no apparent oxidation of the exhaust valve when the engine is operating on lean mixtures of propane.

## 6.2 APPLICATIONS

When designing an engine, or increasing the CR of any existing engine, a considerable saving in operating costs may be realized by using lean fuel-air mixtures of propane as the fuel which also results in fewer oil changes and less engine wear than could be obtained if using gasoline as the fuel, in a lower CR engine. If the engine is operated at maximum thermal efficiency for a fixed speed, less fuel will be required thus resulting in a further saving. At times when greater power is required i.e. for accelerating there will be a momentary reduction in thermal efficiency but the fuel-air ratio may then be re-adjusted to again give maximum thermal efficiency.





### 6.3 RECOMMENDATIONS

Further work should be done in this area to determine the effect of engine speed on the maximum thermal efficiency.

Comparative tests at part throttle should also be investigated.

Since inlet mixture temperature has an effect on thermal efficiency a worthwhile increase in thermal efficiency may be realized by using the latent heat of the liquified propane to cool the inlet fuel-air mixture.

Since engines using lean mixtures are difficult to start in cold weather an investigation should also be conducted to determine the relationship between the fuel-air ratio and minimum fuel-air temperature for starting, and for very cold weather operation.

In order to avoid misfiring at very lean mixtures, and to see if the maximum thermal efficiency may be further increased at leaner mixtures, the effect of a stratified charge, i.e. rich at the spark plug and lean throughout the combustion chamber, should be further investigated using propane as the fuel.

The theoretical analysis should be further improved to take into consideration the effects of heat transfer between the cylinder wall and charge during the entire cycle rather than assume an adiabatic process. Consideration should also be given to the effect of the pressure losses involved during the induction and exhaust processes.





REFERENCES

1. GOODENOUGH, G.A., and BAKER, J.B., "Univ. Ill. Engg. Experimental Station Bulletin 160, (1927).
2. KEENAN, J.H. and KAYE, J., "Gas Tables", John Wiley and Sons Inc., New York, (1948).
3. Hottel, H.C., WILLIAMS, G.C., and SATTERFIELD, C.N. "Thermodynamic Charts for Combustion Processes", John Wiley and Sons Inc., New York, (1949).
4. LICHTY, L.C., "Internal Combustion Engines", McGraw-Hill Co. Inc., New York, (1939), pg. 157.
5. BARBER, E.M., MALIN, J.B., and MIKITA, J.J., "The Elimination of Combustion Knock", Journal of Franklin Research Institute, Vol. 241, April, (1946), pg. 275.
6. KARIN, G.A., "An Analytical Approach to Auto-Ignition and Knock in Internal Combustion Engines", Journal Mechanical Engineering Science, Vol. 6, No. 4, (1964), pg. 353.
7. KING, R.O., "An Investigation of the Mechanism of the Oxidation, Decomposition, Ignition and Detonation of Fuel Vapors and Gases", Defence Research Board, Ottawa, (1959).
8. GLIDEWELL, J.E., "Engines to Digest the Vitamin-Enriched Fuel-Elpeegee", SAE Transactions, Vol. 61, (1953), pg. 131.
9. TAYLOR, C.F., "The Internal Combustion Engine in Theory and Practice", The Technology Press of M.I.T. and John Wiley and Sons Inc., New York, (1960), pgs. 82 and 127.
10. ADAMS, W.E. and BOLDT, K., "What Engines Say About Propane Fuel Mixtures", SAE Transactions, (1965). pg. 718.
11. LAY, J.E., "Thermodynamics", C.E. Merrill Books Inc., Columbus, Ohio, (1963), pg. 745.
12. LEWIS, A.D., "Gas Power Dynamics", D. Van Nostrand Co. Inc., Princeton, New Jersey, (1962), pgs. 518 and 521.



13. Ibid. pg. 528.
14. NATIONAL BUREAU OF STANDARDS, "Selected Values of Properties of Hydrocarbons", Circular C 461, U.S. Dept. of Commerce, (1946), pg. 150.
15. S.A.E. Engine Test Code, "Nonturbocharged Spark Ignition and Diesel", SAEJ 816, (1962.)
16. KEENAN, J.H. and KEYES, F.G., "Thermodynamic Properties of Steam", John Wiley and Sons, Inc., New York, (1936.)
17. MESSERSMITH, C.W., WARNER, C.F. and OLSEN, R.A., "Mechanical Engineering Laboratory", 2nd Edition, John Wiley and Sons, Inc., (1958), pg. 88.
18. PERRY, R.H., CHILTON, C.H. and KIRKPATRICK, S.D., "Chemical Engineers Handbook", 4th Edition, McGraw-Hill Co. Ltd., New York, (1963), pg. 386.

#### BIBLIOGRAPHY

1. LICHTY, L.C., "Thermodynamics", McGraw-Hill Book Co. Inc., New York, (1948).
2. DENNY, L.C., LUXON, L.L. and HALL, B.E., "Handbook Butane-Propane Gases - 4th Ed", Chilton Co., Los Angeles, Calif. (1962).
3. VAN WYLEN, G.J., "Thermodynamics", John Wiley and Sons, Inc., New York, (1962).





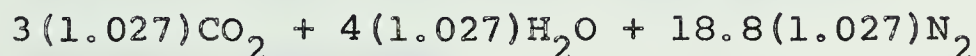
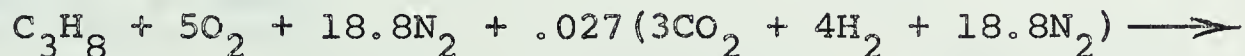
## APPENDIX A

SAMPLE THEORETICAL CALCULATION

Based on the equations of Chapter II and assuming 100% theoretical air, a compression ratio of 9.0 and the fuel and air entering at  $536.6^{\circ}\text{R}$ .

Note: U's and  $\phi$ 's are taken from table [11] if listed in the table.

For the initial calculation assume the residual gas fraction = .027 and  $T_5 = 2300^{\circ}\text{R}$ .  
from equation 2.2-2 -



$$\begin{aligned}\text{Moles of charge} &= 1 + 5 + 18.8 + 0.27(3 + 4 + 18.8) \\ &= 24.8 + .027(25.8) \\ &= 24.8 + .697 = 25.497 \text{ moles}\end{aligned}$$

$$\begin{aligned}\text{Moles of products} &= (3 + 4 + 18.8)1.027 \\ &= (25.8)1.027 = 26.497 \text{ moles}\end{aligned}$$

from equation 2.2-3 -

$$\begin{aligned}U_1 &= H_{\text{fuel}} + H_{\text{O}_2} + H_{\text{N}_2} + U_{\text{res.gas}} - M(1.986)T_1 \left(1 - \frac{1}{\text{CR}}\right) \\ &= 5(83) + 18.8(81) + 23.8(1066) + 180 + 1066 + U_{\text{res.gas}}\end{aligned}$$



$$\begin{aligned}
 & - M(1.986)T_1 \left(\frac{8}{9}\right) \\
 & = 28,551 + U_{\text{res}} - M(1.986)T_1 \left(\frac{8}{9}\right)
 \end{aligned}$$

Energy of residual gas -

$$U_{\text{CO}_2} = 3(.027) 17,680 = 1430$$

$$U_{\text{H}_2\text{O}} = 4(.027) 12,835 = 1388$$

$$U_{\text{N}_2} = 18.8(.027) 9,817 = \underline{4980}$$

$$U_{\text{res}} = \underline{7798 \text{ BTU}}$$

$$\underline{\text{Try } T_1 = 600^\circ}$$

$$\begin{aligned}
 U_1 & = 28,551 + 7798 - 25.497(1.986) \frac{8}{9}(600) \\
 & = 36,349 - 45.0(600) \\
 & = 36,349 - 27,000 = \underline{9,349 \text{ BTU}}
 \end{aligned}$$

Considering mixture at 600

$$\begin{aligned}
 U_{\text{C}_3\text{H}_8} & = .272(600 - 520) + .0160(600^2 - 520^2) - \frac{543}{3 \times 10^8} \\
 & \quad (600^2 - 520^2) \\
 & = .272(80) + .0160(1120)80 - \frac{543}{3 \times 10^2} (216 - 141) \\
 & = 21.8 + 143.3 - 134.0 \\
 & = \underline{1412.8 \text{ BTU}}
 \end{aligned}$$



$$U_{O_2} = 5(402) = 2010$$

$$U_{N_2} = 18.8(1.027)395 = (19.3)395 = 7430$$

$$U_{CO_2} = 3(.027)570 = (.081)570 = 46$$

$$U_{H_2O} = 4(.027)490 = (.108)490 = \underline{53}$$

$$\sum U_1 = \underline{10,952} \text{ BTU}$$

Try  $T_1 = 580^\circ$

$$U_1 = 36,349 - 45.0(580) = 36,349 - 26,100 = 10,249 \text{ BTU}$$

Consider mixture at  $580^\circ$

$$U_{C_3H_8} = .272(60) + .0160(1100)60 - \frac{543}{3 \times 10^2} (194 - 141)$$

$$= 16.3 + 105.9 - 97.7 = 977.6$$

$$U_{O_2} = 5(301) = 1505$$

$$U_{N_2} = 19.3(295) = 5690$$

$$U_{CO_2} = .081(424) = 34.4$$

$$U_{H_2O} = .108(490) = \underline{53}$$

$$\sum U = \underline{8260.0} \text{ BTU}$$

$\therefore T_1$  is between  $580$  and  $600^\circ R$ . Do a linear interpolation to get  $T_1$ .





$$\frac{DT}{10,249 - 8260} = \frac{20 - DT}{10,952 - 9349}$$

$$DT = \frac{20(1989)}{1989 + 1603} = \frac{20(1989)}{3592} = 11.1$$

$$\therefore T_1 = 580 + 11 = \underline{\underline{591^\circ\text{R}}}$$

Adiabatic compression from  $T_1$  to  $T_2$

$$\phi_{\text{C}_3\text{H}_8} = .272 \ln \frac{591}{520} + .0320(591 - 520) - \frac{543}{2 \times 10^8} (591^2 - 520^2)$$

$$= .272 \ln 1.138 + .0320(71) - \frac{543}{2 \times 10^8} (1111)71$$

$$= .0351 + 2.27 - .214 = 2.091$$

$$\phi_{\text{O}_2} = 5 \left( .56 + \frac{11}{21} (.75 - .56) \right) = 5(.56 + .10) = 5(.66) = 3.30$$

$$\phi_{\text{N}_2} = 19.3 \left( .54 + \frac{11}{20} (.72 - .54) \right) = 19.3(.54 + .10)$$

$$= 19.3(.64) = 12.33$$

$$\phi_{\text{CO}_2} = .081 \left( .77 + \frac{11}{20} (1.02 - .77) \right) = .081(.77 + .138)$$

$$= .081(.908) = .07$$

$$\phi_{\text{H}_2\text{O}} = .108 \left( .71 + \frac{11}{20} (.94 - .71) \right) = .108(.71 + .126)$$

$$= .108(.836) = .09$$

$$\sum \phi_{591} = \underline{\underline{17.88}}$$



Try  $T_2 = 1200$

$$\begin{aligned}
 \phi_{C_3H_8} &= .272 \ln \frac{1200}{520} + .0320(1200 - 520) - \frac{543}{3 \times 10^8} (1200^2 - 520^2) \\
 &= .272 \ln 2.31 + .0320(680) - \frac{543}{3 \times 10^8} (1720)680 \\
 &= .228 + 21.8 - 3.18 \\
 &= 18.85
 \end{aligned}$$

$$\phi_{O_2} = 5(4.50) = 22.50$$

$$\phi_{N_2} = 19.3(4.25) = 83.00$$

$$\phi_{CO_2} = .081(6.91) = .56$$

$$\phi_{H_2O} = .108(5.31) = .57$$

$$\sum \phi_{1200} = \underline{125.48}$$

$$\Delta S = \sum \phi_{1200} - \sum \phi_{591} - 1.986(M) \ln CR$$

$$= 125.48 - 17.88 - 1.986(25.497) \ln 9$$

$$= 125.48 - 17.88 - 111.2'$$

$$= 125.48 - 129.08 = \underline{-3.60 \text{ BTU}}$$

∴  $T_2$  assumed too low

Try  $T_2 = 1300$

$$\phi_{C_3H_8} = .272 \ln \frac{1300}{520} + .0320(1300 - 520) - \frac{543}{2 \times 10^8} (1300^2 - 520^2)$$





$$= .272 \ln 2.5 + .0320(780) - \frac{543}{2 \times 10^8} (1820) 780$$

$$= .249 + 24.9 - 3.86 = 21.29$$

$$\phi_{O_2} = 5(4.98) = 24.9$$

$$\phi_{N_2} = 19.3(4.68) = 90.2$$

$$\phi_{CO_2} = .081(7.69) = .62$$

$$\phi_{H_2O} = .108(5.85) = \underline{.63}$$

$$\sum \phi_{1300} = \underline{137.64}$$

$$\Delta s = 137.64 - 17.88 - 111.2$$

$$= 137.64 - 129.08 = \underline{8.56 \text{ BTU}}$$

Linear interpolation to get  $T_2$

$$DT = \frac{100(3.60)}{3.60 + 8.56} = \frac{360}{12.16} = 29.6$$

$$\therefore T_2 = 1200 + 30 = \underline{\underline{1230^\circ R}}$$

Determine the energy of mixture at  $1230^\circ$

$$U_{C_3H_8} = .272T_2 + .016T^2 - \frac{543}{3 \times 10^8} T_3$$

$$= .272(1230 - 520) + .016(1230^2 - 520^2) - \frac{543}{3 \times 10^8}$$

$$(1230^3 - 520^3)$$

$$= .272(710) + .016(1750)710 - \frac{543}{3 \times 10^2} (1860 - 163)$$



$$= .272(710) + .016(1750)710 - \frac{543}{300} (1697)$$

$$= 193 + 19,870 - 3077 = 16,986 \text{ BTU}$$

$$U_{O_2} = 5 \left( 3675 + .3(4263 - 3675) \right) = 5(3851) = 19,240$$

$$U_{N_2} = 19.3 \left( 3461 + .3(3996 - 3461) \right) = 19.3(3622) = 69,900$$

$$U_{CO_2} = .081 \left( 5736 + .3(6721 - 5736) \right) = .081(6032) = 488$$

$$U_{H_2O} = .108 \left( 4339 + .3(5030 - 4339) \right) = .108(4546) = 491$$

$$U_2 = \underline{107,105 \text{ BTU}}$$

$$CE_{C_3H_8} = 878,822 \text{ B/mole}$$

$$\therefore \text{ Total energy} = 878,822 + 107,105 = \underline{985,927 \text{ BTU}}$$

Substitute into equation 2.2-11 and add like terms.

Assume  $T_3 = 5200^\circ R$

<u>Product</u>	<u>Numerical Terms</u>	<u>x terms</u>	<u>y terms</u>
3.081(x)CO		90,200	
3.081(1-x)CO <sub>2</sub>	166,000	-166,000	
4.108(y)H <sub>2</sub>			111,200
4.108(1-y)H <sub>2</sub> O	172,500		-172,500
$\left[ \frac{3}{2}(x) + \frac{4}{2}(y) \right] (1.027)O_2$		47,900	63,900
19.3N <sub>2</sub>	559,000		
$\sum$	<u>897,500</u>	<u>-27,900(x)</u>	<u>2,600(y)</u>



$$CE_{CO} = 3(1.027)(x) 121,181 = 373,000 (x)$$

$$CE_{H_2} = 4(1.027)(y) 103,486 = 424,500 (y)$$

Energy balance gives: -

$$985,927 = 897,500 - 27,900(x) + 2,600(y) + 373,000(x) + 424,500(y)$$

$$\therefore 88,427 = 345,100(x) + 427,100(y)$$

$$\therefore y = \frac{88,427 - 345,100(x)}{427,100}$$

$$= 0.2065 - 0.808x$$

From the tables  $\left[ 12 \right] \log K_{WG} = 0.829$

$$\therefore K_{WG} = 6.75$$

Substitute into equation 2.2-13

$$\therefore y = \frac{x}{6.75 - 5.75x}$$

Equating y's

$$y = 0.2065 - 0.808x = \frac{x}{6.75 - 5.75x}$$

$$\therefore (0.2065 - 0.808x)(6.75 - 5.75x) = x$$

$$1.393 - 5.45x - 1.189x + 4.65x^2 = x$$

$$\therefore 4.65x^2 - 7.639x + 1.393 = 0$$

$$x = \frac{7.639 - \sqrt{(7.639)^2 - 4(4.65)1.393}}{2(4.65)}$$





$$= \frac{7.639 - \sqrt{58.3 - 25.9}}{2(4.65)}$$

$$= \frac{7.639 - 5.69}{2(4.65)}$$

$$= \frac{1.949}{2(4.65)} = \underline{0.2097}$$

$$\therefore y = 0.2065 - 0.808(0.2097)$$

$$= 0.2065 - 0.1692 = \underline{0.0373}$$

Obtain  $P_2$  from  $P_2 = \frac{CR(T_2)(P_1)}{T_1}$

$$P_2 = \frac{9(1230)(1)}{591} = \underline{\underline{18.73 \text{ atm.}}}$$

Obtain  $K_{CO_2}$ , using equation 2.2-8

$$K_{CO_2} = \left( \frac{x}{1-x} \right)^2 \left[ \frac{3}{2}(1+f)x + \frac{4}{2}(1+f)y \right] \frac{P_2 \cdot T_3}{M_2 \cdot T_2}$$

$$= \left( \frac{0.2097}{1 - 0.2097} \right)^2 \left[ \frac{3.081}{2} (.2097) + \frac{4.108}{2} (.0373) \right]$$

$$\frac{18.73(5200)}{25.497(1230)}$$

$$= \left( \frac{0.2097}{0.7903} \right)^2 \left[ 0.322 + 0.0765 \right] \frac{18.73(5200)}{25.497(1230)}$$

$$= (.265)^2 (.3958) \frac{18.73(5200)}{25.497(1230)} = \underline{\underline{.0861}}$$

From the Tables  $\left[ 12 \right] \log K_{CO_2} = -1.32$



$$K_{\text{CO}_2} = \underline{0.048}$$

∴  $T_3$  assumed too low

$$\underline{\text{Try } T_3 = 5400}$$

<u>Product</u>	<u>Numerical Terms</u>	<u>x terms</u>	<u>y terms</u>
3(1.027) (x) CO		94,300	
3(1.027) (1-x) CO <sub>2</sub>	174,000	-174,000	
4(1.027) (y) H <sub>2</sub>			117,000
4(1.027) (1-y) H <sub>2</sub> O	182,000		-182,000
$\left[ \frac{3}{2}(x) + \frac{4}{2}(y) \right] (1.027) \text{ O}_2$		50,200	66,900
19.3 N <sub>2</sub>	585,000		
$\Sigma$	941,000	-29,500(x)	1,900(y)

Energy balance gives:-

$$985,927 = 941,000 - 29,500(x) + 1,900(y) + 373,000(x) + 424,500(y)$$

$$\therefore 44,927 = 343,500(x) + 426,400(y)$$

$$\therefore y = \frac{44,927 - 343,500(x)}{426,400}$$

$$= 0.1052 - 0.805(x)$$

$$\text{From Tables } [12] \log K_{\text{WG}} = 0.840$$

$$\therefore K_{\text{WG}} = 7.06$$





$$\therefore y = \frac{x}{7.06 - 6.06(x)}$$

Equating y's

$$y = 0.1052 - 0.805x = \frac{x}{7.06 - 6.06x}$$

$$\therefore (0.1052 - 0.805x)(7.06 - 6.06x) = x$$

$$0.743 - 5.68x - 0.638x + 4.88x^2 = x$$

$$\therefore 4.88x^2 - 7.318x + 0.743 = 0$$

$$x = \frac{7.318 - \sqrt{(7.318)^2 - 4(4.88)0.743}}{2(4.88)}$$

$$= \frac{7.318 - \sqrt{53.5 - 14.5}}{2(4.88)}$$

$$= \frac{7.318 - 6.24}{2(4.88)} = \frac{1.078}{2(4.88)} = \underline{0.1102}$$

$$y = 0.1052 - 0.805(0.1102)$$

$$= 0.1052 - 0.0887 = \underline{0.0165}$$

$$\therefore K_{CO_2} = \left( \frac{0.1102}{1 - 0.1102} \right)^2 \left[ \frac{3.981}{2} (.1102) + \frac{4.108}{2} (.0165) \right]$$

$$\frac{18.73(5400)}{25.497(1230)}$$

$$= \left( \frac{0.1102}{0.8898} \right)^2 \left[ 0.1699 + 0.0338 \right] \frac{18.73(5400)}{25.497(1230)}$$

$$= (0.125)^2 \left[ 0.2037 \right] \frac{18.73(5400)}{25.497(1230)} = \underline{0.01027}$$

$$\frac{1}{2}(\frac{1}{2} - \frac{1}{2}) = 0$$

By definition

$$\frac{1}{2}(\frac{1}{2} - \frac{1}{2}) = 0$$

$$\frac{1}{2}(\frac{1}{2} - \frac{1}{2}) = 0$$

$$\frac{1}{2}(\frac{1}{2} - \frac{1}{2}) = 0$$

$$\frac{1}{2}(\frac{1}{2} - \frac{1}{2}) = 0$$

$$\frac{1}{2}(\frac{1}{2} - \frac{1}{2}) = 0$$

$$\frac{1}{2}(\frac{1}{2} - \frac{1}{2}) = 0$$

$$\frac{1}{2}(\frac{1}{2} - \frac{1}{2}) = 0$$

$$\frac{1}{2}(\frac{1}{2} - \frac{1}{2}) = 0$$

$$\frac{1}{2}(\frac{1}{2} - \frac{1}{2}) = 0$$

$$\frac{1}{2}(\frac{1}{2} - \frac{1}{2}) = 0$$

From Tables  $\left[ 12 \right] \log K_{\text{CO}_2} = -0.94$

$$\therefore K_{\text{CO}_2} = \underline{0.115}$$

$$\therefore T_3 = 5400^\circ\text{R is too high}$$

Do a linear interpolation to obtain  $T_3$ ,  $x_3$  and  $y_3$ .

$$\frac{DT}{0.0861 - 0.048} = \frac{200 - DT}{0.115 - 0.01027}$$

$$\therefore DT = \frac{0.0381(200)}{0.0381 + 0.10473} = \frac{0.0381(200)}{0.14283}$$

$$= 53.4$$

$$\therefore T_3 = 5200 + 53.4 = \underline{\underline{5253.4^\circ\text{R}}}$$

$$x_3 = 0.2097 - \frac{53.4}{200} (0.2097 - 0.1102) = .2097 - .0266$$

$$= \underline{\underline{0.1831}}$$

$$y_3 = 0.0373 - \frac{53.4}{200} (0.0373 - 0.0165) = .0373 - .0055$$

$$= \underline{\underline{0.0318}}$$

Entropy at  $T_3$

Using equation 2.2-14

$$s_3 = \sum \phi - \sum MR \ln pp + \frac{M_{\text{CO}} C_{\text{E}}^{\text{CO}}}{T_3} + \frac{M_{\text{H}_2} C_{\text{E}}^{\text{H}_2}}{T_3}$$

$$\phi_{\text{CO}_2} = 3.081(1 - .1831) \left[ 27.98 + \frac{253}{500} (29.51 - 27.98) \right]$$

$$= 3.081(0.8169) \left[ 27.98 + 0.774 \right]$$



$$= 3.081(0.8169)(28.754) = 72.2$$

$$\phi_{\text{CO}} = 3.081(0.1831) \left[ 17.72 + \frac{253}{500}(18.57 - 17.72) \right]$$

$$= 3.081(0.1831) [17.72 + 0.43]$$

$$= 3.081(0.1831)(18.15) = 10.22$$

$$\phi_{\text{H}_2\text{O}} = 4.108(1 - .0318) \left[ 22.42 + \frac{253}{500}(23.65 - 22.42) \right]$$

$$= 4.108(1 - .0318)(22.42 + 0.622)$$

$$= 4.108(0.9682)(23.042) = 91.6$$

$$\phi_{\text{H}_2} = 4.108(0.0318) \left[ 16.81 + \frac{253}{500}(17.65 - 16.81) \right]$$

$$= 4.108(0.0318)(16.81 + 0.424)$$

$$= 4.108(0.0318)(17.234) = 2.25$$

$$\phi_{\text{O}_2} = \left[ \frac{3.081}{2}(0.1831) + \frac{4.108}{2}(0.0318) \right] \left[ 18.49 + \frac{253}{500}(19.38 - 18.49) \right]$$

$$= (0.282 + 0.0645)(18.49 + 0.45)$$

$$= 0.3465(18.94) = 6.57$$

$$\phi_{\text{N}_2} = 19.3 \left[ 17.54 + \frac{253}{500}(18.38 - 17.54) \right]$$

$$= 19.3(17.54 - 0.424) = 19.3(17.964) = 346.8$$

$$\sum \phi = \underline{529.64} \text{ BTU}$$

$$P_3 = \frac{M_3}{M_2} \cdot \frac{T_3}{T_2} \cdot P_2$$





$$M_3 = 3.081 + 4.108 + 19.3 + 0.3465 = \underline{26.8355} \text{ moles}$$

$$\therefore P_3 = \frac{26.8355}{25.497} \cdot \frac{5253}{1230} \cdot 18.73 = \underline{84.3} \text{ atm.}$$

<u>Constituent</u>	<u>pp</u>	<u>ln pp</u>	<u>1.986(M) ln pp</u>
3.081(0.8169)CO <sub>2</sub>	7.90	2.065	10.31
3.081(0.1831)CO	1.77	0.572	0.64
4.108(0.9682)H <sub>2</sub> O	12.46	2.52	19.83
4.108(0.0318)H <sub>2</sub>	0.41	-0.891	-0.231
0.3465O <sub>2</sub>	1.09	0.0862	0.059
19.30N <sub>2</sub>	60.60	4.11	157.4
$\Sigma$			188.01

$$\begin{aligned} \therefore s_3 &= 529.64 - 188.01 + \frac{3.081(.1831)121,181}{5253} \\ &\quad + \frac{4.108(.0318)103,486}{5253} \\ &= 529.64 - 188.01 + 13.00 + 2.57 \\ &= \underline{357.20} \text{ BTU} \end{aligned}$$

To find T<sub>4</sub>

Assume T<sub>4</sub> = 3300 °R

$$\text{from Tables, } \left[ 12 \right], \log K_{\text{CO}_2} = -7.08 \text{ and } \log K_{\text{WG}} = 0.593$$

$$\therefore K_{\text{CO}_2} = 8.32 \times 10^{-8} \quad K_{\text{WG}} = 3.92$$



Try  $x = 0.006$

Substituting in equation 2.2-15

$$\begin{aligned}
 K_{\text{CO}_2} &= \left( \frac{0.006}{0.994} \right)^2 \left[ \frac{3.081(.006)}{2} + \frac{4.108(.006)}{2(3.92 - 2.92(.006))} \right] \frac{3300}{25.497(591)} \\
 &= 4.01 \times 10^{-5} \left[ 0.00924 + \frac{4.108(0.003)}{3.92 - 0.0175} \right] \frac{3300}{25.497(591)} \\
 &= 4.01 \times 10^{-5} \left[ 0.00924 + 0.00315 \right] 0.219 \\
 &= 4.01 \times 10^{-5} \left[ 0.01239 \right] 0.219 \\
 &= \underline{1.09 \times 10^{-7}}
 \end{aligned}$$

Try  $x = 0.0057$

$$\begin{aligned}
 K_{\text{CO}_2} &= \left( \frac{0.0057}{0.9943} \right)^2 \left[ \frac{3.081(.0057)}{2} + \frac{4.108(.0057)}{2(3.92 - 2.92(.0057))} \right] 0.219 \\
 &= 3.28 \times 10^{-5} \left[ 0.00876 + \frac{4.108(.0057)}{2(3.92 - .0166)} \right] 0.219 \\
 &= 3.28 \times 10^{-5} \left[ 0.00876 + 0.00299 \right] 0.219 \\
 &= 3.28 \times 10^{-5} \left[ 0.01175 \right] 0.219 \\
 &= \underline{8.43 \times 10^{-8}}
 \end{aligned}$$

Try  $x = 0.00568$

$$\begin{aligned}
 K_{\text{CO}_2} &= \left( \frac{0.00568}{0.99422} \right)^2 \left[ \frac{3.081}{2} (.00568) + \frac{4.108(.00568)}{2(3.903)} \right] 0.219 \\
 &= 3.26 \times 10^{-5} \left[ 0.00874 + 0.00298 \right] 0.219
 \end{aligned}$$





$$= 3.26 \times 10^{-5} (0.01172) 0.219 = \underline{8.35 \times 10^{-8}}$$

$$\text{so } x = \underline{0.00568}$$

$$\therefore y = \frac{0.00568}{3.92 - 2.92(0.00568)} = \frac{0.00568}{3.92 - .0166}$$

$$= \frac{0.00568}{3.9034} = \underline{0.00145}$$

$$\phi_{\text{CO}_2} = 3.081(0.99432) \frac{43.76}{2} = 67.1$$

$$\phi_{\text{CO}} = 3.081(0.00568) \frac{28.15}{2} = 0.246$$

$$\phi_{\text{H}_2\text{O}} = 4.108(0.99854) \frac{34.49}{2} = 70.6$$

$$\phi_{\text{H}_2} = 4.108(0.00145) 13.32 = 0.079$$

$$\phi_{\text{O}_2} = 0.01172(14.69) = 0.172$$

$$\phi_{\text{N}_2} = 19.30 \left( \frac{27.87}{2} \right) = \underline{268.8}$$

$$\sum \phi = 407.00 \text{ BTU}$$

$$M_4 = 3.081 + 4.108 + 0.01172 + 19.3 = \underline{26.501} \text{ moles}$$

$$P_4 = \frac{26.501}{25.497} \cdot \frac{3300(1)}{591} = \underline{5.82} \text{ atm.}$$



<u>Constituent</u>	<u>pp</u>	<u>ln pp</u>	<u>1.986 (M) ln pp</u>
3.081(0.99432)CO <sub>2</sub>	0.672	-0.397	-2.415
3.081(0.00568)CO	0.00384	-5.56	-0.193
4.108(0.99854)H <sub>2</sub> O	0.900	-0.105	-0.855
4.108(0.00145)H <sub>2</sub>	0.00131	-6.63	-0.078
0.01172 O <sub>2</sub>	0.00258	-5.96	-0.139
19.30 N <sub>2</sub>	4.24	1.445	55.4

$$\sum 1.986 (M) \ln pp = \underline{51.72 \text{ BTU}}$$

$$\begin{aligned} \therefore s_4 &= 407.00 - 51.72 + \frac{3.081(.00568)121,200}{3300} \\ &\quad + \frac{4.108(.00145)103,500}{3300} \\ &= 407.00 - 51.72 + 0.64 + 0.19 = \underline{356.11 \text{ BTU}} \end{aligned}$$

$\therefore T_4$  assumed too low

Assume  $T_4 = 3400^\circ\text{R}$

From Tables [12],  $\log K_{\text{CO}_2} = -6.60$  and  $\log K_{\text{WG}} = 0.616$

$$\therefore K_{\text{CO}_2} = 2.52 \times 10^{-7} \text{ and } K_{\text{WG}} = 4.13$$

Try  $x = 0.008$

$$\begin{aligned} K_{\text{CO}_2} &= \left( \frac{0.0082}{0.9918} \right)^2 \left[ \frac{3.081(.0082)}{2} + \frac{4.108(.008)}{2(4.13 - 3.13(.0082))} \right] \frac{3400}{25.497(591)} \\ &= 6.5 \times 10^{-5} \left[ 0.0123 + \frac{0.0164}{4.13 - 0.025} \right] 0.226 \end{aligned}$$



$$\begin{aligned}
&= 6.5 \times 10^{-5} \left[ 0.0123 + 0.0040 \right] 0.226 \\
&= 6.5 \times 10^{-5} (0.0163) 0.226 = \underline{2.40 \times 10^{-7}}
\end{aligned}$$

Try  $x = 0.0082$

$$\begin{aligned}
K_{\text{CO}_2} &= \left( \frac{0.0082}{0.9918} \right)^2 \left[ \frac{3.081(0.0082)}{2} + \frac{4.108(0.0082)}{2(4.13 - 3.13(0.0082))} \right] 0.226 \\
&= 6.84 \times 10^{-5} \left[ 0.0126 + 0.0041 \right] 0.226 \\
&= 6.84 \times 10^{-5} (0.0167) 0.226 = \underline{2.58 \times 10^{-7}}
\end{aligned}$$

Try  $x = 0.00814$

$$\begin{aligned}
K_{\text{CO}_2} &= \left( \frac{0.00814}{0.99186} \right)^2 \left[ \frac{3.081(0.00814)}{2} + \frac{4.108(0.00814)}{2(4.13 + 3.13(0.00814))} \right] 0.226 \\
&= 6.74 \times 10^{-5} \left[ 0.0125 + 0.0041 \right] 0.226 \\
&= 6.74 \times 10^{-5} (0.0166) 0.226 = \underline{2.53 \times 10^{-7}}
\end{aligned}$$

So  $x = \underline{\underline{0.00814}}$

$$\begin{aligned}
y &= \frac{0.00814}{4.13 - 3.13(0.00814)} = \frac{0.00814}{4.13 - 0.0255} \\
&= \frac{0.00814}{4.105} = \underline{\underline{0.00198}}
\end{aligned}$$

$$\phi_{\text{CO}_2} = 3.081(0.99186)22.32 = 68.2$$

$$\phi_{\text{CO}} = 3.081(0.00814)14.34 = 0.36$$

$$\phi_{\text{H}_2\text{O}} = 4.108(0.99802)17.61 = 72.2$$

$$\phi_{\text{H}_2} = 4.108(0.00198)13.58 = 0.11$$





$$\phi_{O_2} = 0.0166(14.95) = 0.25$$

$$\phi_{N_2} = 19.30(14.20) = \underline{274.0}$$

$$\sum \phi = \underline{415.12} \text{ BTU}$$

$$M_4 = 3.081 + 4.108 + 19.3 + 0.0166 = \underline{26.506} \text{ moles}$$

$$P_4 = \frac{26.506}{25.497} \cdot \frac{3400}{591} (1) = \underline{5.97} \text{ atm.}$$

<u>Constituent</u>	<u>pp</u>	<u>ln pp</u>	<u>1.986(M) ln pp</u>
3.081(0.99185)CO <sub>2</sub>	0.689	-0.372	-2.26
3.081(0.00814)CO	0.00565	-5.17	-0.257
4.108(0.99802)H <sub>2</sub> O	0.923	-0.080	-0.650
4.108(0.00198)H <sub>2</sub>	0.00183	-6.30	-0.102
0.0166 O <sub>2</sub>	0.00374	-5.59	-0.184
19.30 N <sub>2</sub>	4.35	1.47	<u>56.2</u>
		$\sum =$	<u>52.75</u> BTU

$$\begin{aligned} \therefore s_4 &= 415.12 - 52.75 + \frac{3.081(.00814)121,200}{3400} \\ &\quad + \frac{4.108(.00198)103,500}{3400} \\ &= 415.12 - 52.75 + 0.89 + 0.32 = \underline{363.58} \text{ BTU} \end{aligned}$$

$\therefore T_4$  assumed too high.

By linear interpolation obtain  $T_4$ ,  $x_4$  and  $y_4$  between 3300 and 3400 °R.



$$\frac{DT}{357.20 - 356.11} = \frac{100 - DT}{363.58 - 357.20}$$

$$\therefore DT = \frac{1.09(100)}{1.09 + 6.38} = \frac{1.09(100)}{7.47} = 14.6$$

$$\therefore T_4 = 3300 + 14.6 = \underline{\underline{3315^\circ\text{R}}}$$

$$\begin{aligned} x_4 &= 0.00568 + \frac{14.6}{100}(.00814 - .00568) = .00568 + .00036 \\ &= \underline{\underline{0.00604}} \end{aligned}$$

$$\begin{aligned} y_4 &= 0.00145 + \frac{14.6}{100}(.00198 - .00145) = .00145 + .00008 \\ &= \underline{\underline{0.00153}} \end{aligned}$$

$$s_5 = \sum \phi_5 - \sum MR \ln pp$$

$$\text{No. of moles} = 3.081 + 4.108 + 19.30 = \underline{\underline{26.489 \text{ moles}}}$$

$$\underline{\text{Try } T_5 = 2300^\circ\text{R}}$$

$$\phi_{\text{CO}_2} = 3.081(16.81) = 51.9$$

$$\phi_{\text{H}_2\text{O}} = 4.108(13.22) = 54.3$$

$$\phi_{\text{N}_2} = 19.30(10.92) = \underline{\underline{210.7}}$$

$$\sum \phi = \underline{\underline{316.9 \text{ BTU}}}$$

Constituent	pp	$\ln pp$	$1.986(M) \ln pp$
3.081CO <sub>2</sub>	0.1162	-2.15	-13.16
4.108H <sub>2</sub> O	0.1548	-1.863	-15.19
19.3N <sub>2</sub>	0.729	-0.316	<u>-12.10</u>

$$\sum = \underline{\underline{-40.45 \text{ BTU}}}$$





$$\therefore s_5 = 316.9 + 40.45 = \underline{357.35} \text{ BTU}$$

$$\therefore \text{Take } T_5 = 2300^\circ \text{R}$$

$$f = \frac{V_2}{V_5} = \frac{M_1 (T_1)}{M_5 (CR) T_5}$$

$$= \frac{25.497(591)}{26.489(9)2300} = \underline{0.0275}$$

$T_5$  is found to be as assumed but  $f$  is slightly high 0.0275 rather than 0.027 as assumed so the calculations should be re-done using  $f = 0.0275$ , for greater accuracy.

To determine thermal efficiency

Substitute into equation 2.2-17

$$u_1 = u_{\text{mix } 600} - \frac{9}{20} (u_{\text{mix } 600} - u_{\text{mix } 580})$$

$$= 10,249 - \frac{9}{20} (10249 - 9349)$$

$$= 10,249 - \frac{9}{20} (900) = 10,249 - 405 = \underline{9,844} \text{ BTU}$$

$$u_2 = \underline{107,105} \text{ BTU}$$

To find  $u_3$

$$u_{\text{CO}_2} = 3.081(1 - .1831) \left[ 53,963 + \frac{53.4}{200} (56,569 - 53,963) \right]$$

$$= 3.081(.8169) \left[ 53,963 + \frac{53.4}{200} (2606) \right]$$

$$= 3.081(.8169) (53,963 + 695) = 3.081(.8169) 54,658$$



$$= \underline{137,500}$$

$$\begin{aligned} u_{\text{CO}} &= 3.081(.1831) \left[ 29,287 + \frac{53.4}{200} (30,665 - 29,287) \right] \\ &= 3.081(.1831) (29,287 + 370) = 3.081(.1831) 29,657 \\ &= \underline{16,780} \end{aligned}$$

$$\begin{aligned} u_{\text{H}_2\text{O}} &= 4.108(1 - .0318) \left[ 42,087 + \frac{53.4}{200} (44,307 - 42,087) \right] \\ &= 4.108(0.9682) (42,087 + 592) = 4.108(.9682) 42,679 \\ &= \underline{169,400} \end{aligned}$$

$$\begin{aligned} u_{\text{H}_2} &= 4.108(0.0318) \left[ 27,156 + \frac{53.4}{200} (28,508 - 27,156) \right] \\ &= 4.108(.0318) (27,156 + 361) = 4.108(.0318) 27,517 \\ &= \underline{3,580} \end{aligned}$$

$$\begin{aligned} u_{\text{O}_2} &= 0.3465 \left[ 31,115 + \frac{53.4}{200} (32,622 - 31,115) \right] \\ &= 0.3465 (31,115 + 401) = 0.3465 (31,516) \\ &= \underline{10,900} \end{aligned}$$

$$\begin{aligned} u_{\text{N}_2} &= 19.30 \left[ 28,961 + \frac{53.4}{200} (30,337 - 28,961) \right] \\ &= 19.30 (28,961 + 367) = 19.3 (29,328) \\ &= \underline{566,000} \end{aligned}$$

$$u_3 = \underline{904,160} \text{ BTU}$$

To find  $u_4$

$$u_{\text{CO}_2} = 3.081(1 - .00604) \left[ 29,750 + \frac{15}{100} (30,991 - 29,750) \right]$$



$$= 3.081(0.99395)(29,750 + 186) = 3.081(.99395)29,936$$

$$= \underline{92,900}$$

$$u_{CO} = 3.081(.00604)(16,414 + 100) = 3.081(.00604)16,514$$

$$= \underline{308}$$

$$u_{H_2O} = 4.108(.99847)(22,066 + 149) = 4.108(.99847)22,215$$

$$= \underline{91,300}$$

$$u_{H_2} = 4.108(.00153)(14,921 + 91) = 4.108(.00153)15,012$$

$$= \underline{94}$$

$$u_{O_2} = \left[ \frac{3.081}{2} (.00604) + \frac{4.108}{2} (.00153) \right] (17,386 + 104)$$

$$= (0.00933 + 0.00314)(17,490) = 0.01247(17,490)$$

$$= \underline{218}$$

$$u_{N_2} = 19.30(16,199 + 98) = 19.30(16,297) = \underline{316,300}$$

$$u_4 = \underline{\underline{501,120 \text{ BTU}}}$$

$$\therefore \eta = \frac{(904,160 - 501,120) - (107,105 - 9,844)}{44.094(19,929)} \cdot 100$$

$$= \frac{(403,040 - 97,261)}{44.094(19,929)} \cdot 100$$

$$= \frac{(305,779)100}{44.094(19,929)} = \underline{\underline{34.7\%}}$$

To find m.e.p.

Substitute into equation 2.2-16

$$v_1 = \frac{mRT_1}{P_1} = \frac{25.497(1545)591}{14.7(144)} = 110,000 \text{ ft}^3$$





$$v_2 = \frac{v_1}{CR} = \frac{110,000}{9} = 12,200 \text{ ft}^3$$

$$\begin{aligned} \therefore \text{ m.e.p.} &= \frac{305,770(778)}{(110,000 - 12,200)(144)} = \frac{305,779(778)}{97,800(144)} \\ &= \underline{\underline{169}} \text{ psi.} \end{aligned}$$



## APPENDIX B

## PROGRAM FOR THEORETICAL ANALYSIS

```

$JOB          525015    G.R. POND
$TIME         30,3000
$IBJOB POND
$IBFTC POND    NODECK
C  ** OTTO CYCLE CALCULATIONS  **
C
  DATA FU1,FU2/5HC8H18,4HC3H8/
  REAL N2,MP,LS,MCU,MCU2,MOS,MW,MU2
  KI=1
  READ(5,51) XC
  IF(XC.GT.4.) GO TO 2
  FU=FU2
  XC=3.
  XH=8.
  CR=8.0
  CEF=878822.
  HEAT=44.098*19929.
  UCG=180.0
  GO TO 4
2  KI=2
  FU=FU1
  XC=8.
  XH=18.
  CR=7.0
  CEF=2201618.
  HEAT=2361226.
  UCG=674.0
4  XH2=XH/2.0
  XO2=(XH2+2.0*XC)/2.
  XN2=3.76/XO2
  WRITE(6,52) FU
6  PC=0.80
  TT1=920.
  TT2=1350.
  F=0.03
  CZ=XH2
  WRITE(6,54) CR
  M=1
  N=15
  DO 11 J=M,N
  LI=0
  PE=100.*PC
  WRITE(6,53) PE
  MOS=PC*XC2
  IF(PC.LT.0.999) GO TO 8
C
C  IF EXCESS AIR OR 100 PERCENT AIR
  MO2=XC
  MCO=0.000
  MCO2=XC
  IF(PC.LT.1.001) GO TO 12

```



```

EXC=(2.*XO2*PC-2.*MO2-XH2)/2.
GO TO 14

```

```

C
C IF AIR LESS THAN 100 PERCENT CO2 DISSOC TO CO
  8  MOS=PC*XO2
    MO2=MOS-XH/4.
    MCO=2.0*(XC-MO2)
    IF(MCO.GE.0.0000) GO TO 10
    MCO=0.00000
  10  MCO2=MO2-MCO/2.
  12  EXC=0.000000000

```

```

C
  14  CONTINUE
    PO2=PC*XO2
    PN2=PC*XN2
    XLS=1.00+PO2+PN2
    MW=XC*12.0+XH*1.008

```

```

C
C INITIAL COND@S TO FIND T1 - FUEL MIXTURE PLUS CLEARANCE GAS
C ASSUME FUEL TEMP = 537.
C ** CONSTANT PRESSURE ADIABATIC PROCESS **
C U1 = FU5+HCG+HGF-PV/J+Q ASSUME Q=0.0
    FA=MW/(32.0*PO2+28.0*PN2)
    HCG=PO2*83.0+PN2*81.0+(XLS-1.0)*1066.0
    HG=UCG+1066.0

```

```

C
C CXHY+PC*(XO2+XN2)=MCO2*CO2+XH2*H2O+MCO*CO+XN2*PC*N2+EXC*O2

```

```

C
C FIRST TRIAL ASSUMING NO DISSOCIATION AND FOLLOWING
  T1=TT1+80.
  T2=TT2+180.
  T4=3600.
  T5=2500.
  X=0.0
  Y=0.0
  LF=0
  LK=0
  AZ=MCO2
  BZ=MCO
  DZ=EXC
  EZ=PN2
  16  MCO2=AZ
    MCO=BZ
    XH2=CZ
    EXC=DZ
    PN2=EZ

```

```

C
C SUM OF MOLES ON RIGHT SIDE OF EQUATION (PRODUCTS)
  Z=1.+F
  ZA=MCO2*Z
  ZB=MCO*Z
  ZC=XH2*Z
  ZD=EXC*Z
  ZE=PN2*Z
  MCO2=ZA
  MCO=ZB

```





```

      XH2=ZC
      EXC=ZD
      PN2=ZE
13  XRS=XH2+MCO+EXC+PN2+MCO2
C
C  NO. OF MOLES IN CHARGE
15  XCH=XRS-1,
      WRITE(3,60) MCO2,MCO,XH2,EXC,PN2,XRS,XCH,ZA,AZ
      KO=0
17  CALL ENERGY (T5,XC,UCO2,UCO,UO2,UN2,UH2O,UH2,UFU)
      UA=MCC2*(X*UCO+(1.00000-X)*UCO2)
      UB=XH2*(Y*UH2+(1.00000-Y)*UH2O)
      UC=(X*MCO2/2.0+Y*XH2/2.+EXC)*UO2
      UD=PN2*UN2+MCO*UCO
C
C   $P(V_1-V_0)=RT(V_1-V_0) = RT/V_1(V_1-V_2) = RT(1-1/CR)$ 
      FUH=F*(UA+UB+UC+UD)+HCG+HG
      R=1.9839*XCH*(1.0-1.0/CR)
18  U1=FUH-R*T1
C
C  CHECK U1 BY CONSIDERING GAS AT T1
C  USENS=F*JCL+(UAIR+UFU)
C
      CALL ENERGY (T1,XC,UCO2,UCO,UO2,UN2,UH2O,UH2,UFU)
      UA=MCO2*(X*UCO+(1.00000-X)*UCO2)
      UB=XH2*(Y*UH2+(1.00000-Y)*UH2O)
      UC=(X*MCO2/2.0+Y*XH2/2.+EXC)*UO2
      UD=PN2*UN2+MCO*UCO
      UE=PO2*UO2+PN2*UN2+UFU
      USENS=UE+(UA+UB+UC+UD)*F
      PT1=T1
      CALL TEMP(T1,USENS,U1,DIF,KO)
      TT=ABS((PT1-T1)/T1)
      IF(TT.GT.0.01) GO TO 17
      IF(KO.LT.2.OR.DIF.GT.0.0) GO TO 18
      V2=V1/CR
      V1=1545.*T1*XCH/(144.*14.7)
      KO=0
C
C  ADIABATIC COMPRESSION TO T2 - AT CONSTANT ENTROPY
C
C  ENTROPY OF FUEL
20  IF(XC.LT.4.) GO TO 22
      SFU=5.93*ALOG(T2/T1)+0.061*(T2-T1)
      GO TO 24
22  SFU=0.272*ALOG(T2/T1)+.0320*(T2-T1)-(543.*(T2**2.0-T1**2.0)/200000
1000.)
C
24  A=1.0/T2
      B=1.0/T1
      SCO2=F*MCO2*(1.-X)*(14.3*ALOG(T2/T1)+6530.*(A-B)-705000.*(A**2.0-B
1**2.0))
      SCU=F*(MCO+MCO2*X)*(7.47*ALOG(T2/T1)+3290.*(A-B)-535000.*(A**2.0-B
1**2.0))

```



```

SO2=(MOS+F*(EXC+X*MCU/2.+Y*XH2/2.))* (9.529*ALOG(T2/T1)+173.0*2.0*
1(A**0.5-B**0.5)-1530.0*(A-B))
SH2O=F*XH2*(1.-Y)*(17.87*ALOG(T2/T1)+597.*2.*(A**0.5-B**0.5)-7500.
1*(A-B))
SN2=PN2*(1.0+F)*(7.48*ALOG(T2/T1)+3470.*(A-B)-580000.*(A**2.-B**2.
1))
SH2=F*XH2*Y*(3.77*ALOG(T2/T1)+0.000578*(T2-T1)-40.*(A**0.5-B**0.5)
1)
SUM=SFU+SCO2+SCO+SO2+SN2+SH2O+SH2
SU=XCH*1.9859*ALOG(CR)

```

C

```

PT2=T2
26 CALL TEMP (T2,SUM,SU,DIF,KO)
P2=CR*1.0*T2/T1
IF(KO.LT.2.OR.DIF.GT.0.0) GO TO 20
CALL ENERGY(T2,XC,UCO2,UCO,UO2,UN2,UH2O,UH2,UFU)
UA=MCO2*UCO2
UB=XH2*UH2O
UC=EXC*UO2
UD=PN2*UN2+MC)*UCO
UE=PO2*UC2+PN2*UN2+UFU
U2=F*(JA+UB+UC+UD)+UE
LS=U2+CEF
CALL CBUSTN (XC,LS,PC,MCU2,XH2,PN2,EXC,MCU,X3,Y3,T3,KL,T2,P2,XCH,X
1M)
XC3=XRS+XM

```

C

C REVERSIBLE ADIABATIC EXPANSION -T3 TO T4 - AT CONSTANT ENTROPY  
C X AND Y BOTH DECREASE DUE TO TEMPERATURE DROP

C

```

C ENTROPY AT T3
PP3=P3
P3=XC3*T3*P2/(XCH*T2)
27 CALL ENTROP(T3,X3,Y3,MCU2,MCU,EXC,XH2,PN2,P3,XC3,S3)
V3=XC3*1545.*T3/(P3*14.7*144.)
V4=CR*V3

```

C

C TO FIND T4

```

28 LS=0.0
PT4=P4
KO=0
LL=18
29 IF(T4.GT.3000.) GO TO 30
X4=0.0
Y4=0.0
XM=0.0
TT4=T4-10.
T4=TT4
GO TO 31
30 KL=LL+1
CALL CBUSTN (XC,LS,PC,MCU2,XH2,XN2,EXC,MCU,X4,Y4,T4,KL,T1,P3,XCH,X
1M)
31 LL=KL

```





```

C   TO FIND P4
    XCH4=XRS+XM
    P4=XCH4*T4/(XCH*T1)
    PS4=S4
    CALL ENTROP(T4,X4,Y4,MCO2,MCO,EXC,XH2,PN2,P4,XCH4,S4)
    IF(S4.GT.S3) GO TO 29
    IT=100.*(S3-S4)/(PS4-S4)
    KT=T4
    T4=IT+KT+10
33  CALL ENTROP(T4,X,Y,MCO2,MCO,EXC,XH2,PN2,P4,XCH4,S4)
    IF(T4.LT.1000.) GO TO 35
    KO=2
    CALL TEMP(T4,S4,S3,DIF,KO)
    IF(DIF.GT.0.0) GO TO 33
35  CONTINUE
C
C   EXHAUST PROCESS AND CLEARANCE GAS
    V4=XCH4*1545.*T4/(P4*144.*14.7)
    DV=V4-V1
    IF(ABS(DV).LT.50.) GO TO 32
C
C   ISENTROPIC EXPANSION TO T5 AT 14.7 PSI
C   ASSUMING NO DISSOCIATION AT T5
32  P5=1.00
    PT5=T5
    X5=0.0
    Y5=0.0
    T5=PT5+250.
    XCH5=XRS
    KO=0
38  CALL ENTROP(T5,X5,Y5,MCO2,MCO,EXC,XH2,PN2,P5,XCH5,S5)
    CALL TEMP(T5,S5,S3,DIF,KO)
    IF(KO.LT.2.OR.DIF.GE.0.0) GO TO 38
    TT=ABS((PT5-T5)/T5)
    IF(TT.LT.0.01) GO TO 39
    IT1=T1
    T1=IT1+50
    GO TO 17
39  V5=XCH5*1545.*T5/(14.7*144.)
    FF=T1*(XCH/(CR*T5*XCH5))
    DF=ABS((F-FF)/FF)
    LF=1
    GF=V2/V5
    F=FF
    IF(DF.LT.0.01) GO TO 40
    IT1=T1
    T1=IT1+50
    GO TO 16
C
C   TO FIND THERMAL EFFIC. AND BMEP
40  CALL ENERGY (T3,XC,UCO2,UCO,UO2,UN2,UH2O,UH2,UFO)
    WRITE(6,65) PE,T1,T2,P2,T3,P3,T4,P4,X3,Y3,X4,Y4,F
    UA=MCO2*(X3*UCO+(1.00000-X3)*UCO2)
    UB=XH2*(Y3*UH2+(1.00000-Y3)*UH2O)
    UC=(X3*MCO2/2.0+Y3*XH2/2.+EXC)*UO2
    UD=PN2*UN2+MCO*UCO

```





```

U3=UA+UB+UC+UD
CALL ENERGY (T4,XC,UCO2,UCO,UO2,UN2,UH2O,UH2,UFO)
UA=MCO2*(X4*UCO+(1.00000-X4)*UCO2)
UB=XH2*(Y4*UH2+(1.00000-Y4)*UH2O)
UC=(X4*MCO2/2.+Y4*XH2/2.+EXC)*UO2
UD=PN2*UN2+MCO*UCO
U4=UA+UB+UC+UD
WORK=U3-U4+U1-U2
ETA=100.*WORK/HEAT
V1=XCH*1545.*T1/(14.7*144.)
V2=V1/CR
BMEP=WORK*778./((144.)*(V1-V2))
WRITE(6,57) U1,U2,U3,U4,WORK,ETA,V1,BMEP
TT1=T1
TT2=T2
TT4=T4
TT5=T5
DPC=PC+0.10
PC=DPC
11 CONTINUE
PCR=CR
CR=PCR+1.0
IF(CR.LE.11.0) GO TO 6
GO TO(2,99),KI
51 FORMAT(F6.0)
52 FORMAT(1H1,40X,8H FUEL IS,2X,A6)
53 FORMAT(1HK,15X,13H PERCENT AIR=,F7.2)
54 FORMAT(1HJ,20X,20H COMPRESSION RATIO =,F7.2)
57 FORMAT(1H ,8F16.2)
60 FORMAT(1HJ,6F15.4,3F12.4)
65 FORMAT(1HK,9F9.2,5F10.6)
99 STOP
END

```

\$IBFTC ENTROP DECK

```

SUBROUTINE ENTROP(T3,X,Y,MCO2,MCO,EXC,XH2,PN2,P,XC,S)
REAL MCO2,MCO
T=520.0
A=1.0/T3
B=1.0/520.0
IF(T3.LE.600.) WRITE(6,59) T3,X,Y,MCO2,MCO,EXC,XH2,P,XC
TLOG=ALOG(T3/T)
SCO2=MCO2*(1.-X)*(16.2*TLOG+6530.*(A-B)-705000.*(A**2.0-B**2.0))
SCO=(MCO+MCO2*X)*(9.46*TLOG+3290.*(A-B)-535000.*(A**2.0-B**2.0))
SO2=(EXC+X*MCO2/2.+Y*XH2/2.)*(11.515*TLOG+173.0*2.0*(A**0.5-B**0.5)
1)-1530.*(A-B))
SH2O=XH2*(1.-Y)*(19.86*TLOG+597.*2.*(A**0.5-B**0.5)-7500.*(A-B))
SN2=PN2*(9.47*TLOG+3470.*(A-B)-580000.*(A**2.-B**2.))
SH2=XH2*Y*(5.76*TLOG+0.000578*(T3-T)-40.*(A**0.5-B**0.5))
IF(T3.LE.4000.) GO TO 27
EH2=SH2-0.00033*((T3-T)-4000.*TLOG)*XH2*Y
SH2=EH2
IF(T3.LE.5000.) GO TO :7
EO2=SO2+0.00005*((T3-T)-4000.+TLOG)*(EXC+X*MCO2/2.+Y*XH2/2.)

```



```

      S02=E02
27  SUM=SC02+SC0+S02+SN2+SH2O+SH2
C
C  TO FIND PARTIAL PRESSURES OF CONSTITUENTS AT T3
      A=(1.0-X)*MCO2
      B=(EXC+X*MCO2/2.+Y*XH2/2.)
      C=(1.00-Y)*XH2
      D=(MCO+MCO2*X)
      E=PN2
      G=XH2*Y
      AP=A*P/XC
      BP=B*P/XC

      CP=C*P/XC
      DP=D*P/XC
      EP=E*P/XC
      GP=G*P/XC
C  SUM OF 1.9859(M)LN(P)
      IF(AP.LE.0.0) GO TO 21
      SA=A*ALOG(AP)
      GO TO 22
21  SA=0.0
22  IF(CP.LE.0.0) GO TO 23
      SC=C*ALOG(CP)
      GO TO 24
23  SC=0.0
24  IF(EP.LE.0.0) GO TO 25
      SE=E*ALOG(EP)
      GO TO 26
25  SE=0.0
26  IF(BP.LE.0.0) GO TO 28
      SB=B*ALOG(BP)
      GO TO 29
28  SB=0.0
29  IF(DP.LE.0.0) GO TO 31
      SD=D*ALOG(DP)
      GO TO 32
31  SD=0.0
32  IF(GP.LE.0.0) GO TO 33
      SG=G*ALOG(GP)
      GO TO 34
33  SG=0.0
34  SUS=1.9859*(SA+SB+SC+SD+SE+SG)
      SDIS=(MCO2*X*121181.+XH2*Y*103486.)/T3
      S=SUM-SUS+SDIS
      RETURN
59  FORMAT(1H ,8F16.2)
      END

```

1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027, 2028, 2029, 2030, 2031, 2032, 2033, 2034, 2035, 2036, 2037, 2038, 2039, 2040, 2041, 2042, 2043, 2044, 2045, 2046, 2047, 2048, 2049, 2050, 2051, 2052, 2053, 2054, 2055, 2056, 2057, 2058, 2059, 2060, 2061, 2062, 2063, 2064, 2065, 2066, 2067, 2068, 2069, 2070, 2071, 2072, 2073, 2074, 2075, 2076, 2077, 2078, 2079, 2080, 2081, 2082, 2083, 2084, 2085, 2086, 2087, 2088, 2089, 2090, 2091, 2092, 2093, 2094, 2095, 2096, 2097, 2098, 2099, 2100, 2101, 2102, 2103, 2104, 2105, 2106, 2107, 2108, 2109, 2110, 2111, 2112, 2113, 2114, 2115, 2116, 2117, 2118, 2119, 2120, 2121, 2122, 2123, 2124, 2125, 2126, 2127, 2128, 2129, 2130, 2131, 2132, 2133, 2134, 2135, 2136, 2137, 2138, 2139, 2140, 2141, 2142, 2143, 2144, 2145, 2146, 2147, 2148, 2149, 2150, 2151, 2152, 2153, 2154, 2155, 2156, 2157, 2158, 2159, 2160, 2161, 2162, 2163, 2164, 2165, 2166, 2167, 2168, 2169, 2170, 2171, 2172, 2173, 2174, 2175, 2176, 2177, 2178, 2179, 2180, 2181, 2182, 2183, 2184, 2185, 2186, 2187, 2188, 2189, 2190, 2191, 2192, 2193, 2194, 2195, 2196, 2197, 2198, 2199, 2200, 2201, 2202, 2203, 2204, 2205, 2206, 2207, 2208, 2209, 2210, 2211, 2212, 2213, 2214, 2215, 2216, 2217, 2218, 2219, 2220, 2221, 2222, 2223, 2224, 2225, 2226, 2227, 2228, 2229, 2230, 2231, 2232, 2233, 2234, 2235, 2236, 2237, 2238, 2239, 2240, 2241, 2242, 2243, 2244, 2245, 2246, 2247, 2248, 2249, 2250, 2251, 2252, 2253, 2254, 2255, 2256, 2257, 2258, 2259, 2260, 2261, 2262, 2263, 2264, 2265, 2266, 2267, 2268, 2269, 2270, 2271, 2272, 2273, 2274, 2275, 2276, 2277, 2278, 2279, 2280, 2281, 2282, 2283, 2284, 2285, 2286, 2287, 2288, 2289, 2290, 2291, 2292, 2293, 2294, 2295, 2296, 2297, 2298, 2299, 2300, 2301, 2302, 2303, 2304, 2305, 2306, 2307, 2308, 2309, 2310, 2311, 2312, 2313, 2314, 2315, 2316, 2317, 2318, 2319, 2320, 2321, 2322, 2323, 2324, 2325, 2326, 2327, 2328, 2329, 2330, 2331, 2332, 2333, 2334, 2335, 2336, 2337, 2338, 2339, 2340, 2341, 2342, 2343, 2344, 2345, 2346, 2347, 2348, 2349, 2350, 2351, 2352, 2353, 2354, 2355, 2356, 2357, 2358, 2359, 2360, 2361, 2362, 2363, 2364, 2365, 2366, 2367, 2368, 2369, 2370, 2371, 2372, 2373, 2374, 2375, 2376, 2377, 2378, 2379, 2380, 2381, 2382, 2383, 2384, 2385, 2386, 2387, 2388, 2389, 2390, 2391, 2392, 2393, 2394, 2395, 2396, 2397, 2398, 2399, 2400, 2401, 2402, 2403, 2404, 2405, 2406, 2407, 2408, 2409, 2410, 2411, 2412, 2413, 2414, 2415, 2416, 2417, 2418, 2419, 2420, 2421, 2422, 2423, 2424, 2425, 2426, 2427, 2428, 2429, 2430, 2431, 2432, 2433, 2434, 2435, 2436, 2437, 2438, 2439, 2440, 2441, 2442, 2443, 2444, 2445, 2446, 2447, 2448, 2449, 2450, 2451, 2452, 2453, 2454, 2455, 2456, 2457, 2458, 2459, 2460, 2461, 2462, 2463, 2464, 2465, 2466, 2467, 2468, 2469, 2470, 2471, 2472, 2473, 2474, 2475, 2476, 2477, 2478, 2479, 2480, 2481, 2482, 2483, 2484, 2485, 2486, 2487, 2488, 2489, 2490, 2491, 2492, 2493, 2494, 2495, 2496, 2497, 2498, 2499, 2500, 2501, 2502, 2503, 2504, 2505, 2506, 2507, 2508, 2509, 2510, 2511, 2512, 2513, 2514, 2515, 2516, 2517, 2518, 2519, 2520, 2521, 2522, 2523, 2524, 2525, 2526, 2527, 2528, 2529, 2530, 2531, 2532, 2533, 2534, 2535, 2536, 2537, 2538, 2539, 2540, 2541, 2542, 2543, 2544, 2545, 2546, 2547, 2548, 2549, 2550, 2551, 2552, 2553, 2554, 2555, 2556, 2557, 2558, 2559, 2560, 2561, 2562, 2563, 2564, 2565, 2566, 2567, 2568, 2569, 2570, 2571, 2572, 2573, 2574, 2575, 2576, 2577, 2578, 2579, 2580, 2581, 2582, 2583, 2584, 2585, 2586, 2587, 2588, 2589, 2590, 2591, 2592, 2593, 2594, 2595, 2596, 2597, 2598, 2599, 2600, 2601, 2602, 2603, 2604, 2605, 2606, 2607, 2608, 2609, 2610, 2611, 2612, 2613, 2614, 2615, 2616, 2617, 2618, 2619, 2620, 2621, 2622, 2623, 2624, 2625, 2626, 2627, 2628, 2629, 2630, 2631, 2632, 2633, 2634, 2635, 2636, 2637, 2638, 2639, 2640, 2641, 2642, 2643, 2644, 2645, 2646, 2647, 2648, 2649, 2650, 2651, 2652, 2653, 2654, 2655, 2656, 2657, 2658, 2659, 2660, 2661, 2662, 2663, 2664, 2665, 2666, 2667, 2668, 2669, 2670, 2671, 2672, 2673, 2674, 2675, 2676, 2677, 2678, 2679, 26

$$V(\mathbf{r}) = \frac{1}{2} \left( \frac{1}{r} + \frac{1}{r'} \right) = \frac{1}{2} \left( \frac{1}{r} + \frac{1}{r''} \right)$$

— 100 —

\* 2002-2003

$$- \frac{1}{2} \frac{d^2 \phi}{d\tau^2} = 1$$
$$x^2 + x - 4$$
$$U \setminus \{y\} = U$$

7.  $\sqrt{45} = 3\sqrt{5}$

184-7203

$$\lambda \in \mathbb{C} \setminus \{0\}$$
$$(1 - \frac{1}{2}) \times (1 - \frac{1}{2}) = \frac{1}{4}$$

1951 (1952) 1953 (1954) 1955 (1956) 1957 (1958) 1959 (1960) 1961 (1962) 1963 (1964) 1965 (1966) 1967 (1968) 1969 (1970) 1971 (1972) 1973 (1974) 1975 (1976) 1977 (1978) 1979 (1980) 1981 (1982) 1983 (1984) 1985 (1986) 1987 (1988) 1989 (1990) 1991 (1992) 1993 (1994) 1995 (1996) 1997 (1998) 1999 (2000) 2001 (2002) 2003 (2004) 2005 (2006) 2007 (2008) 2009 (2010) 2011 (2012) 2013 (2014) 2015 (2016) 2017 (2018) 2019 (2020) 2021 (2022) 2023 (2024) 2025 (2026) 2027 (2028) 2029 (2030) 2031 (2032) 2033 (2034) 2035 (2036) 2037 (2038) 2039 (2040) 2041 (2042) 2043 (2044) 2045 (2046) 2047 (2048) 2049 (2050) 2051 (2052) 2053 (2054) 2055 (2056) 2057 (2058) 2059 (2060) 2061 (2062) 2063 (2064) 2065 (2066) 2067 (2068) 2069 (2070) 2071 (2072) 2073 (2074) 2075 (2076) 2077 (2078) 2079 (2080) 2081 (2082) 2083 (2084) 2085 (2086) 2087 (2088) 2089 (2090) 2091 (2092) 2093 (2094) 2095 (2096) 2097 (2098) 2099 (2100) 2101 (2102) 2103 (2104) 2105 (2106) 2107 (2108) 2109 (2110) 2111 (2112) 2113 (2114) 2115 (2116) 2117 (2118) 2119 (2120) 2121 (2122) 2123 (2124) 2125 (2126) 2127 (2128) 2129 (2130) 2131 (2132) 2133 (2134) 2135 (2136) 2137 (2138) 2139 (2140) 2141 (2142) 2143 (2144) 2145 (2146) 2147 (2148) 2149 (2150) 2151 (2152) 2153 (2154) 2155 (2156) 2157 (2158) 2159 (2160) 2161 (2162) 2163 (2164) 2165 (2166) 2167 (2168) 2169 (2170) 2171 (2172) 2173 (2174) 2175 (2176) 2177 (2178) 2179 (2180) 2181 (2182) 2183 (2184) 2185 (2186) 2187 (2188) 2189 (2190) 2191 (2192) 2193 (2194) 2195 (2196) 2197 (2198) 2199 (2200) 2201 (2202) 2203 (2204) 2205 (2206) 2207 (2208) 2209 (2210) 2211 (2212) 2213 (2214) 2215 (2216) 2217 (2218) 2219 (2220) 2221 (2222) 2223 (2224) 2225 (2226) 2227 (2228) 2229 (2230) 2231 (2232) 2233 (2234) 2235 (2236) 2237 (2238) 2239 (2240) 2241 (2242) 2243 (2244) 2245 (2246) 2247 (2248) 2249 (2250) 2251 (2252) 2253 (2254) 2255 (2256) 2257 (2258) 2259 (2260) 2261 (2262) 2263 (2264) 2265 (2266) 2267 (2268) 2269 (2270) 2271 (2272) 2273 (2274) 2275 (2276) 2277 (2278) 2279 (2280) 2281 (2282) 2283 (2284) 2285 (2286) 2287 (2288) 2289 (2290) 2291 (2292) 2293 (2294) 2295 (2296) 2297 (2298) 2299 (2300) 2301 (2302) 2303 (2304) 2305 (2306) 2307 (2308) 2309 (2310) 2311 (2312) 2313 (2314) 2315 (2316) 2317 (2318) 2319 (2320) 2321 (2322) 2323 (2324) 2325 (2326) 2327 (2328) 2329 (2330) 2331 (2332) 2333 (2334) 2335 (2336) 2337 (2338) 2339 (2340) 2341 (2342) 2343 (2344) 2345 (2346) 2347 (2348) 2349 (2350) 2351 (2352) 2353 (2354) 2355 (2356) 2357 (2358) 2359 (2360) 2361 (2362) 2363 (2364) 2365 (2366) 2367 (2368) 2369 (2370) 2371 (2372) 2373 (2374) 2375 (2376) 2377 (2378) 2379 (2380) 2381 (2382) 2383 (2384) 2385 (2386) 2387 (2388) 2389 (2390) 2391 (2392) 2393 (2394) 2395 (2396) 2397 (2398) 2399 (2400) 2401 (2402) 2403 (2404) 2405 (2406) 2407 (2408) 2409 (2410) 2411 (2412) 2413 (2414) 2415 (2416) 2417 (2418) 2419 (2420) 2421 (2422) 2423 (2424) 2425 (2426) 2427 (2428) 2429 (2430) 2431 (2432) 2433 (2434) 2435 (2436) 2437 (2438) 2439 (2440) 2441 (2442) 2443 (2444) 2445 (2446) 2447 (2448) 2449 (2450) 2451 (2452) 2453 (2454) 2455 (2456) 2457 (2458) 2459 (2460) 2461 (2462) 2463 (2464) 2465 (2466) 2467 (2468) 2469 (2470) 2471 (2472) 2473 (2474) 2475 (2476) 2477 (2478) 2479 (2480) 2481 (2482) 2483 (2484) 2485 (2486) 2487 (2488) 2489 (2490) 2491 (2492) 2493 (2494) 2495 (2496) 2497 (2498) 2499 (2500) 2501 (2502) 2503 (2504) 2505 (2506) 2507 (2508) 2509 (2510) 2511 (2512) 2513 (2514) 2515 (2516) 2517 (2518) 2519 (2520) 2521 (2522) 2523 (2524) 2525 (2526) 2527 (2528) 2529 (2530) 2531 (2532) 2533 (2534) 2535 (2536) 2537 (2538) 2539 (2540) 2541 (2542) 2543 (2544) 2545 (2546) 2547 (2548) 2549 (2550) 2551 (2552) 2553 (2554) 2555 (2556) 2557 (2558) 2559 (2560) 2561 (2562) 2563 (2564) 2565 (2566) 2567 (2568) 2569 (2570) 2571 (2572) 2573 (2574) 2575 (2576) 2577 (2578) 2579 (2580) 2581 (2582) 2583 (2584) 2585 (2586) 2587 (2588) 2589 (2590) 2591 (2592) 2593 (2594) 2595 (2596) 2597 (2598) 2599 (2600) 2601 (2602) 2603 (2604) 2605 (2606) 2607 (2608) 2609 (2610) 2611 (2612) 2613 (2614) 2615 (2616) 2617 (2618) 2619 (2620) 2621 (2622) 2623 (2624) 2625 (2626) 2627 (2628) 2629 (2630) 2631 (2632) 2633 (2634) 2635 (2636) 2637 (2638) 2639 (2640) 2641 (2642) 2643 (2644) 2645 (2646) 2647 (2648) 2649 (2650) 2651 (2652) 2653 (2654) 2655 (2656) 2657 (2658) 2659 (2660) 2661 (2662) 2663 (2664) 2665 (2666) 2667 (2668) 2669 (2670) 2671 (2672) 2673 (2674) 2675 (2676) 2677 (2678) 2679 (2680) 2681 (2682) 2683 (2684) 2685 (2686) 2687 (2688) 2689 (2690) 2691 (2692) 2693 (2694) 26

$$1) \quad \text{a) } \cup \quad \text{b) } \cap \quad \text{c) } \Delta = \{A, B\}$$

1000

15-07-20 (11:00-12:00) 31

$$(4) \quad \lim_{x \rightarrow 0} \frac{1}{x} = \infty$$

15 JUL 52

100

100 (100%)

$$(2) \quad \frac{1}{2} \times 12 = 6$$

95-01-60

 $\Delta = 35$ 

81-21 46-1-31-93131

$$(-1)^{n-1} \frac{1}{n} = \frac{1}{n}$$

15 01 67

2000

18-21-00 (100-35401) 71

$$A = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad B = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

100

12. 45171

1990-1991, 1991-1992, 1992-1993, 1993-1994, 1994-1995, 1995-1996, 1996-1997, 1997-1998, 1998-1999, 1999-2000, 2000-2001, 2001-2002, 2002-2003, 2003-2004, 2004-2005, 2005-2006, 2006-2007, 2007-2008, 2008-2009, 2009-2010, 2010-2011, 2011-2012, 2012-2013, 2013-2014, 2014-2015, 2015-2016, 2016-2017, 2017-2018, 2018-2019, 2019-2020, 2020-2021, 2021-2022, 2022-2023, 2023-2024, 2024-2025, 2025-2026, 2026-2027, 2027-2028, 2028-2029, 2029-2030, 2030-2031, 2031-2032, 2032-2033, 2033-2034, 2034-2035, 2035-2036, 2036-2037, 2037-2038, 2038-2039, 2039-2040, 2040-2041, 2041-2042, 2042-2043, 2043-2044, 2044-2045, 2045-2046, 2046-2047, 2047-2048, 2048-2049, 2049-2050, 2050-2051, 2051-2052, 2052-2053, 2053-2054, 2054-2055, 2055-2056, 2056-2057, 2057-2058, 2058-2059, 2059-2060, 2060-2061, 2061-2062, 2062-2063, 2063-2064, 2064-2065, 2065-2066, 2066-2067, 2067-2068, 2068-2069, 2069-2070, 2070-2071, 2071-2072, 2072-2073, 2073-2074, 2074-2075, 2075-2076, 2076-2077, 2077-2078, 2078-2079, 2079-2080, 2080-2081, 2081-2082, 2082-2083, 2083-2084, 2084-2085, 2085-2086, 2086-2087, 2087-2088, 2088-2089, 2089-2090, 2090-2091, 2091-2092, 2092-2093, 2093-2094, 2094-2095, 2095-2096, 2096-2097, 2097-2098, 2098-2099, 2099-2100, 2100-2101, 2101-2102, 2102-2103, 2103-2104, 2104-2105, 2105-2106, 2106-2107, 2107-2108, 2108-2109, 2109-2110, 2110-2111, 2111-2112, 2112-2113, 2113-2114, 2114-2115, 2115-2116, 2116-2117, 2117-2118, 2118-2119, 2119-2120, 2120-2121, 2121-2122, 2122-2123, 2123-2124, 2124-2125, 2125-2126, 2126-2127, 2127-2128, 2128-2129, 2129-2130, 2130-2131, 2131-2132, 2132-2133, 2133-2134, 2134-2135, 2135-2136, 2136-2137, 2137-2138, 2138-2139, 2139-2140, 2140-2141, 2141-2142, 2142-2143, 2143-2144, 2144-2145, 2145-2146, 2146-2147, 2147-2148, 2148-2149, 2149-2150, 2150-2151, 2151-2152, 2152-2153, 2153-2154, 2154-2155, 2155-2156, 2156-2157, 2157-2158, 2158-2159, 2159-2160, 2160-2161, 2161-2162, 2162-2163, 2163-2164, 2164-2165, 2165-2166, 2166-2167, 2167-2168, 2168-2169, 2169-2170, 2170-2171, 2171-2172, 2172-2173, 2173-2174, 2174-2175, 2175-2176, 2176-2177, 2177-2178, 2178-2179, 2179-2180, 2180-2181, 2181-2182, 2182-2183, 2183-2184, 2184-2185, 2185-2186, 2186-2187, 2187-2188, 2188-2189, 2189-2190, 2190-2191, 2191-2192, 2192-2193, 2193-2194, 2194-2195, 2195-2196, 2196-2197, 2197-2198, 2198-2199, 2199-2200, 2200-2201, 2201-2202, 2202-2203, 2203-2204, 2204-2205, 2205-2206, 2206-2207, 2207-2208, 2208-2209, 2209-2210, 2210-2211, 2211-2212, 2212-2213, 2213-2214, 2214-2215, 2215-2216, 2216-2217, 2217-2218, 2218-2219, 2219-2220, 2220-2221, 2221-2222, 2222-2223, 2223-2224, 2224-2225, 2225-2226, 2226-2227, 2227-2228, 2228-2229, 2229-2230, 2230-2231, 2231-2232, 2232-2233, 2233-2234, 2234-2235, 2235-2236, 2236-2237, 2237-2238, 2238-2239, 2239-2240, 2240-2241, 2241-2242, 2242-2243, 2243-2244, 2244-2245, 2245-2246, 2246-2247, 2247-2248, 2248-2249, 2249-2250, 2250-2251, 2251-2252, 2252-2253, 2253-2254, 2254-2255, 2255-2256, 2256-2257, 2257-2258, 2258-2259, 2259-2260, 2260-2261, 2261-2262, 2262-2263, 2263-2264, 2264-2265, 2265-2266, 2266-2267, 2267-2268, 2268-2269, 2269-2270, 2270-2271, 2271-2272, 2272-2273, 2273-2274, 2274-2275, 2275-2276, 2276-2277, 2277-2278, 2278-2279, 2279-2280, 2280-2281, 2281-2282, 2282-2283, 2283-2284, 2284-2285, 2285-2286, 2286-2287, 2287-2288, 2288-2289, 2289-2290, 2290-2291, 2291-2292, 2292-2293, 2293-2294, 2294-2295, 2295-2296, 2296-2297, 2297-2298, 2298-2299, 2299-2300, 2300-2301, 2301-2302, 2302-2303, 2303-2304, 2304-2305, 2305-2306, 2306-2307, 2307-2308, 2308-2309, 2309-2310, 2310-2311, 2311-2312, 2312-2313, 2313-2314, 2314-2315, 2315-2316, 2316-2317, 2317-2318, 2318-2319, 2319-2320, 2320-2321, 2321-2322, 2322-2323, 2323-2324, 2324-2325, 2325-2326, 2326-2327, 2327-2328, 2328-2329, 2329-2330, 2330-2331, 2331-2332, 2332-2333, 2333-2334, 2334-2335, 2335-2336, 2336-2337, 2337-2338, 2338-2339, 2339-2340, 2340-2341, 2341-2342, 2342-2343, 2343-2344, 2344-2345, 2345-2346, 2346-2347, 2347-2348, 2348-2349, 2349-2350, 2350-2351, 2351-2352, 2352-2353, 2353-2354, 2354-2355, 2355-2356, 2356-2357, 2357-2358, 2358-2359, 2359-2360, 2360-2361, 2361-2362, 23

1000



## \$IBFTC ENERGY DECK

SUBROUTINE ENERGY(T,XC,UCO2,UCO,UO2,UN2,UH2O,UH2,UFU)

C UT-U520=INTEGRAL OF CV\*DT =INT(CV\*(T-520)) CV=CP-1.9859

TE=T-520.0

R=1.0/T

S=1.0/520.0

V=T\*\*2.0

W=520.0\*\*2.0

X=T\*\*0.5

Y=520.0\*\*0.5

UCO2=(16.2-1.9859)\*TE-6530.\*ALOG(T/520.0)-141.\*(R-S)\*10000.

UCO=(9.46-1.9859)\*TE-3290.\*ALOG(T/520.0)-107.\*(R-S)\*10000.

UO2=(11.515-1.9859)\*TE-173.\*2.\*(X-Y)+1530.\*ALOG(T/520.0)

UN2=(9.47-1.9859)\*TE-3470.\*ALOG(T/520.0)-116.\*(R-S)\*10000.

UH2O=(19.86-1.9859)\*TE-597.\*2.\*(X-Y)+7500.\*ALOG(T/520.0)

UH2=(5.76-1.9859)\*TE+0.578\*(V-W)/2000.+40.\*(X-Y)

IF(XC.LT.4.0) GO TO 1

UFU=(7.92-1.9859)\*TE+0.0601\*(V-W)/2.0

GO TO 3

1 UFU=(2.258-1.9859)\*TE+.032\*(V-W)/2.-543.\*((T/100.0)\*\*3.-5.2\*\*3.)/3010.

3 IF(T.LE.4000.0) GO TO 2

UH=UH2-.33\*(.5\*T\*\*2.-4000.\*T)/1000.

UH2=UH

IF(T.LE.5000.0) GO TO 2

UO=UO2+.05\*(.5\*T\*\*2.-4000.\*T)/1000.

UO2=UO

2 RETURN

END

## \$IBFTC TEMP DECK

SUBROUTINE TEMP(T,SUM,SU,DIF,KO)

DIF=SUM-SU

TE=T

IF(KO.GT.0) GO TO 2

IF(DIF.LT.0.0) GO TO 2

IT=(T+5.0)/10.

TE=IT\*10

DT=-100.

GO TO 3

2 IF(KO.EQ.1.AND.DIF.GT.0.0) GO TO 5

IF(KO.EQ.2) GO TO 6

KO=1

DT=10.

DI=DIF

GO TO 3

5 KO=2

6 DT=-1.00

DI=DIF

8 T=TE+DT

RETURN

END

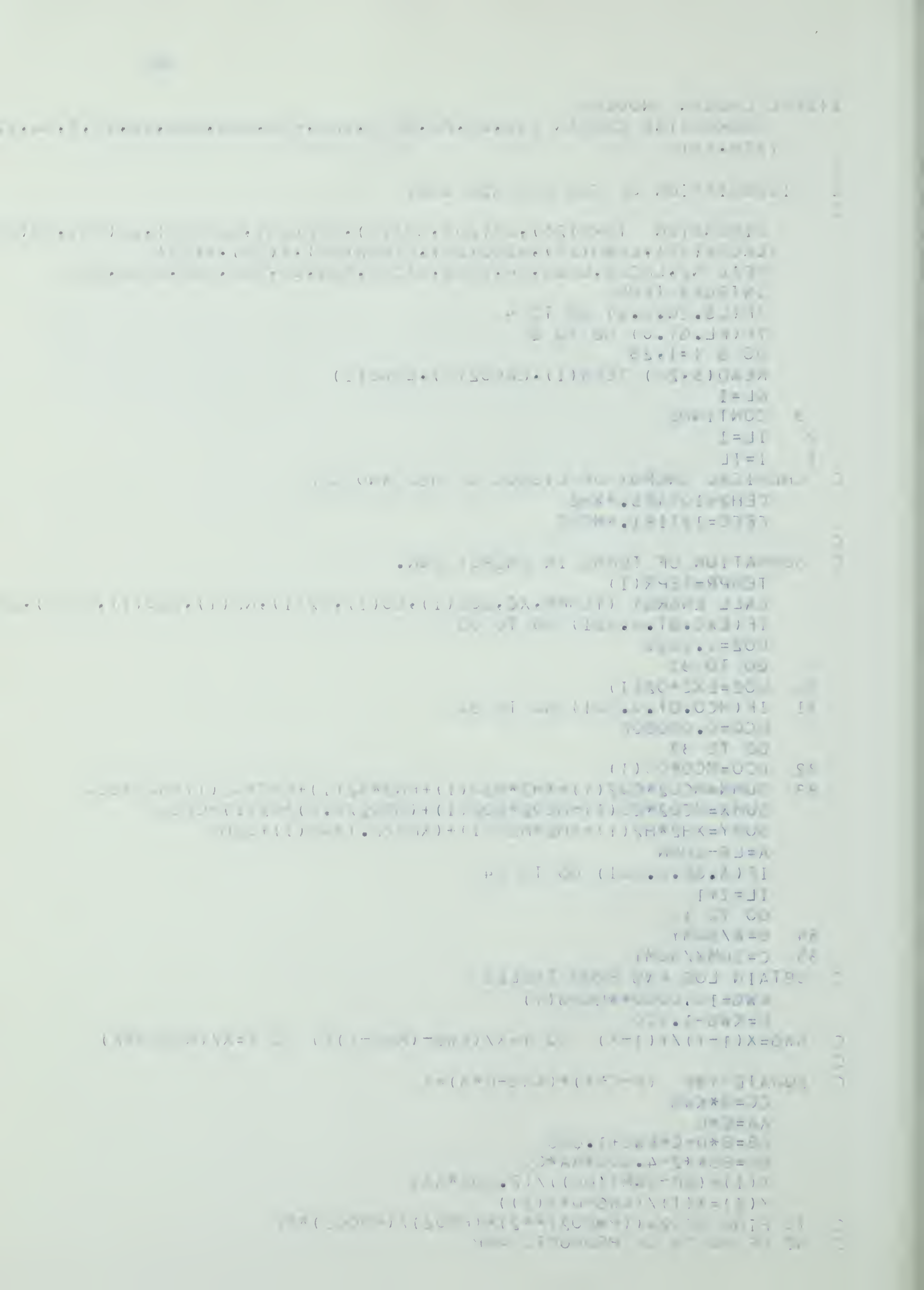




```

$IBFTC CBUSTN  NODECK
      SUBROUTINE CBUSTN (XC,LS,PC,MCO2,XH2,PN2,EXC,MCO,XX,YY,T,KL,T2,P2,
      1XCH,XM)
C
C  DISSOCIATION OF CO2 AND H2O ONLY
C
      DIMENSION  TEPR(25),O2(25),N2(25),CO2(25),H2O(25),H2(50),CO(25),
      1LKCO2(25),LKWG(25),KCO2(25),KTCO2(25),X(25),Y(25)
      REAL N2,LKCO2,LKWG,MP,KCO2,KTCO2,KWG,LS,MO2,MCO,MCO2,MOS
      INTEGER TEPR
      IF(LS.EQ.0.0) GO TO 4
      IF(KL.GT.0) GO TO 2
      DO 3 I=1,23
      READ(5,20) TEPR(I),LKCO2(I),LKWG(I)
      KL=1
3     CONTINUE
2     IL=1
1     I=IL
C  CHEMICAL ENERGY OF DISSOC OF H2O AND CO2
      CEH2=103486.*XH2
      CECO=121181.*MCO2
C
C  SUMMATION OF TERMS IN ENERGY EQN.
      TEMPR=TEPR(I)
      CALL ENERGY (TEMPR,XC,CO2(I),CO(I),O2(I),N2(I),H2O(I),H2(I),UFU)
      IF(EXC.GT.0.001) GO TO 30
      UO2=0.0000
      GO TO 31
30    UO2=EXC*O2(I)
31    IF(MCO.GT.0.001) GO TO 32
      UCO=0.000000
      GO TO 33
32    UCO=MCO*CO(I)
33    SUMN=MCO2*CO2(I)+XH2*H2O(I)+PN2*N2(I)+EXC*O2(I)+UO2+UCO
      SUMX=MCO2*CO(I)-MCO2*CO2(I)+(MCO2/2.0)*O2(I)+CECO
      SUMY=XH2*H2(I)-XH2*H2O(I)+(XH2/2.)*O2(I)+CEH2
      A=LS-SUMN
      IF(A.GE.0.001) GO TO 34
      IL=I+1
      GO TO 1
34    B=A/SUMY
35    C=SUMX/SUMY
C  OBTAIN LOG KWG FROM TABLES
      KWG=10.0000**LKWG(I)
      D=KWG-1.000
C  KWG=X(1-Y)/Y(1-X)  SO Y=X/(KWG-(KWG-1)X)  SO Y=X/(KWG-D*X)
C
C  EQUATE Y@S  (B-C*X)*(KWG-D*X)=X
      CC=B*KWG
      AA=C*D
      BB=B*D+C*KWG+1.000
      DD=BB**2-4.000*AA*CC
      X(I)=(BB-SQRT(DD))/(2.000*AA)
      Y(I)=X(I)/(KWG-D*X(I))
C  TO FIND KCO2=((P@CO2)**2)*(P@O2)/(P@CO2)**2
C  NO OF MOLES OF PRODUCTS =MP

```



```

MP=MCO2+XH2+MCO+EXC+PN2+(MCO2*X(I)+XH2*Y(I))/2.0
R=X(I)**2
S=(1.0000-X(I))**2
W=(MCO2/2.)*X(I)+(XH2/2.0)*Y(I)
TEMPER=TEPR(I)
KCO2(I)=(R*TEMPER*W*P2)/(S*XCH*T2)
KTCO2(I)=10.000**LKCO2(I)
IL=I+1
IF(I.EQ.23) GO TO 12
IF(LS.GT.0.0) GO TO 6
4  I=KL
   KO=0
   XX=0.06
   WX=7000.*XX
   KWG=10.00**LKWG(I)
   D=KWG-1.00
   KTCO2(I)=10.00**LKCO2(I)
   T=TEPR(I)
5  YY=XX/(KWG-D*XX)
   IF(XX.GT.0.1) GO TO 14
   IF(XX.GE.0.00015) GO TO 11
   XX=0.0001
   YY=0.00001
11 A=XX**2.0
   B=(MCO2*XX+XH2*YY)/2.0
   D=(1.0-XX)**2.0
   KCO2(I)=B*T*A/(D*T2*XCH)
   CK=10000000.*KCO2(I)
   TK=10000000.*KTCO2(I)
   CALL TEMP(WX,CK,TK,DIF,KO)
   XX=WX/7000.
   IF(KO.LT.2.OR.DIF.GT.0.0) GO TO 5
   GO TO 14
6  IF(KCO2(I).GT.KTCO2(I)) GO TO 8
   IF(T.LE.3000.) GO TO 14
   PT=TEPR(I)
   PX=X(I)
   PY=Y(I)
   PK=KCO2(I)
   PKT=KTCO2(I)
   PKW=KWG
   PMP=MP
   GO TO 1
8  F=KCO2(I)-KTCO2(I)
   WRITE(6,21) TEPR(I),SUMN,SUMX,SUMY,MP,KCO2(I),KTCO2(I),X(I),Y(I)
   IF(I.GT.1) GO TO 10
   KL=2
   T=5400.
   XX=X(I)
   YY=Y(I)
   WRITE(6,27)
   GO TO 14
10 G=PKT-PK

```





```

      IF(TEPR(I).LT.5000) GO TO 7
      SPA=200.
      GO TO 9
7     SPA=100.
9     IT=F*SPA/(F+G)
      DT=IT
      TT=TEPR(I)
      T=TT+DT+5.0
      U=X(I)-PX
      XX=PX+(SPA-DT)*U/SPA
      V=Y(I)-PY
      YY=PY+(SPA-DT)*V/SPA
      DMP=PMP-MP
      XMP=MP+DMP*DT/SPA
      MP=XMP
      GO TO 14
12    WRITE(6,25)
      KL=2
14    XM=(MCJ2*XX+XH2*YY)/2.0
      RETURN
20    FORMAT(I4,F6.2,F7.3)
21    FORMAT(1HJ,I5,3F12.0,F8.3,4F14.7)
25    FORMAT(1HJ,44H TEMPERATURE BELOW 3000@R MORE DATA REQUIRED)
27    FORMAT(1HJ,14H T3 ABOVE 5400)
      END

```

\$ENTRY            POND  
3.

5400	-0.94	0.840
5200	-1.32	0.829
5000	-1.70	0.816
4900	-1.90	0.810
4800	-2.12	0.803
4700	-2.36	0.795
4600	-2.59	0.787
4500	-2.83	0.779
4400	-3.08	0.770
4300	-3.35	0.760
4200	-3.63	0.748
4100	-3.93	0.736
4000	-4.25	0.723
3900	-4.59	0.709
3800	-4.95	0.693
3700	-5.32	0.676
3600	-5.72	0.658
3500	-6.15	0.638
3400	-6.60	0.616
3300	-7.08	0.593
3200	-7.58	0.570
3100	-8.12	0.545
3000	-8.68	0.520





Variable(s)		FUEL-ATR RATIO AND SPARK RANGE		CR = 9.82		Time Start		12:15		Finish		1:45		
Barometric Pressure		27.480		Ambient Temp. 82°F		Wet Bulb		°F		R. H.		%		
Cooling Water Temp. Start 208 °F, Finish 208 °F		Oil Temp. Start 140°F, Finish 140 °F								Oil Pressure		36		
Special Test Equipment														
<div style="display: flex; justify-content: space-between;"> <div> Oscilloscope Settings  <u>μ strain</u>      Reten </div> <div> Dynamometer Arm </div> </div>														
Heating Valve of Fuel				19,929 BTU/lb		Orifice Size		Coef.						
R.P.M.		Fuel		Intake Air		Exhaust Gas		Dynamometer						
Run No.	Spark Gt	Revs.	Time	Cons.	Temp.	Pres.	Temp.	Δ P	Manif.	Temp.	CO <sub>2</sub>	O <sub>2</sub>	CO	Load
48	5	1116	1.849		78	8.00	82	0.217		803	7.0	2.2	6.4	23.8 lbs.
49	5	1280	2.116		79	6.00	84	0.214		856	9.4	1.7	3.9	24.9 lbs.
50	5	1518	2.554		79	4.00	84	0.214		830	11.3	2.5	0.1	23.4 lbs.
51	10	1934	3.233		80	7.22	85	0.220		703	9.0	6.0	0.0	17.5 lbs.
52	20	2387	4.001		80	1.20	85	0.225		535	8.5	6.9	0.0	9.2 lbs.
Test Crew Duty														
<div style="display: flex; justify-content: space-between;"> <div> FRICTION LOAD = 9.7 lbs. </div> <div> Recorder's Signature _____ </div> <div> Indicator _____ </div> </div>														



## APPENDIX D

SAMPLE CALCULATION OF TEST RESULTSTest No. 5, Run 43

C.R. = 9.77

Spark 20°

Revs 2333

Time 3.845

Fuel Temp. 78°F

Fuel Pressure 2 x 0.68 = 1.32"H<sub>2</sub>O

Air Temp. 83°F

Air-flow Manometer 0.227 in.H<sub>2</sub>OBarometric Pressure = 27.590  
in.Hg.

Cylinder Temp. 585°F

% CO<sub>2</sub> 8.4% O<sub>2</sub> 7.4

% O 0.0

Dyna. Load 10.9 lbs.

Fric. Load 10.1 lbs.

Gas Pressure:  $\frac{1.32 (29.92)}{33.899 (12)} = 0.0971 \text{ in.Hg.}$ Saturation Pressure =  $\left[ .3631 + 8(.01438) \right] \frac{29.92}{14.696}$ =  $\left[ .3631 + .1150 \right] \frac{29.92}{14.696}$ =  $(0.4781) \frac{29.92}{14.696} = 0.973 \text{ in.Hg.}$ 

P = 27.590 + 0.971 - 0.973 = 26.714 in Hg.

0.500 cu. ft. of gas in 3.845 mins.

Correct for Barometric conditions.



$$\text{Vol.} = \frac{.5(26.714)520}{29.92(460+78)} = .431 \text{ ft}^3$$

$$\text{Wt.} = \frac{.431(60)}{8.503(3.845)} = 0.791 \text{ lb/hr.}$$

$$\begin{aligned} \text{Correction factor (CF)} &= \frac{29.90}{27.590} \sqrt{\frac{460 + 78}{545}} \\ &= \frac{29.90}{27.59} \sqrt{0.989} = 1.078 \end{aligned}$$

$$\text{r.p.m.} = \frac{2333}{3.845} = 606 \text{ r.p.m.}$$

$$\text{Torque} = \frac{10.52}{12} (10.9) = 9.56 \text{ ft-lb.}$$

$$\text{BHP} = \frac{2\pi(9.56)606}{33,000} = 1.103 \text{ HP}$$

$$\text{FHP} = 2\pi \left( \frac{10.52}{12} \right) \frac{10.1(606)}{33,000} = 1.022 \text{ HP}$$

$$\text{CIHP} = 1.078 (1.103 + 1.022)$$

$$= 1.078 (2.125) = 2.29 \text{ HP}$$

$$\text{C.B.H.P.} = 2.29 - 1.022 = 1.27 \text{ HP}$$

$$\text{Thermal Effic.}(\eta) = \frac{2.29(2545)100}{19929(.791)} = 37.9\%$$

$$\text{Brake Thermal Effic.} = \frac{1.27(2545)100}{19929(.791)} = 20.5\%$$





$$\text{Mech. Efficiency} = \frac{1.27}{2.29} (100) = 55.5\%$$

$$\text{Fuel/CIHP} = \frac{.791}{2.29} = 0.346 \text{ lb/CIHP}$$

$$\text{Fuel/BHP} = \frac{.791}{1.27} = 0.623 \text{ lb/BHP}$$

$$\text{Air Density} = \frac{27.590 (14.696) 144}{29.92 (538) 53.34} = .0679 \text{ lb/ft}^3$$

$$\text{Head of air} = \frac{.227 (62.4)}{.0679 (12)} = 17.4 \text{ ft. of air}$$

$$\text{Velocity} = 0.62 \sqrt{64.4 (17.4)}$$

$$= 0.62 (33.45) = 20.75 \text{ f.p.s.}$$

$$\text{Flow of air} = \left[ \frac{20.75 \pi (.9983)^2 60 (.0679)}{4 (144)} \right] 1.078$$

$$= \left[ \frac{20.75 \pi (.9966) 60 (.0679)}{4 (144)} \right] 1.078$$

$$= 0.495 \text{ lb/min.}$$

$$\text{Fuel-air Ratio} = \frac{0.791}{0.495 (60)} = 0.0266 \text{ lb.fuel/lb.air}$$

$$\text{Air-fuel Ratio} = \frac{1}{.0266} = 37.6 \text{ lb.air/lb.fuel}$$

the first two terms of the series are

$$\frac{1}{2} \pi^2 \approx 4.9348022$$

$$\frac{1}{2} \pi^2 \approx 4.9348022$$

$$\frac{1}{2} \pi^2 \approx 4.9348022$$

$$\frac{1}{2} \pi^2 \approx 4.9348022$$

$$\frac{1}{2} \pi^2 \approx 4.9348022$$

$$\frac{1}{2} \pi^2 \approx 4.9348022$$

$$\frac{1}{2} \pi^2 \approx 4.9348022$$

$$\frac{1}{2} \pi^2 \approx 4.9348022$$

$$\frac{1}{2} \pi^2 \approx 4.9348022$$

$$\frac{1}{2} \pi^2 \approx 4.9348022$$

$$\frac{1}{2} \pi^2 \approx 4.9348022$$

$$\text{B.m.e.p.} = \frac{33,000(1.27)4(2)}{\pi(3.25)^2(.375)606} = 44.4 \text{ psi}$$

$$\text{I.m.e.p.} = \frac{33,000(2.29)4(2)}{\pi(3.25)^2(.375)606} = 80.1 \text{ psi}$$



## APPENDIX E

## PROGRAM FOR CALCULATION OF TEST DATA

```

$JOB          525015    G.R. POND
$TIME          5,3000
$IBJOB POND
$IBFTC POND    DECK
C  CALCULATIONS FOR C.F.R. ENGINE TEST
  DIMENSION RUN(50),REVS(50),TIME(50),TEMP(50),DP(50),TEM(50),CO2(50
1),O2(50),CO(50),LOAD(50),FRIC(50),RPM(50),LB(50),TUR(50),BHP(50),E
2TA(50),FHP(50),IHP(50),MEFF(50),FU(50),RATIO(50),Z(50),E(50),FA(50
3),BMEP(50),AIR(50),CBHP(50),CMEP(50),FUEL(20),SET(50),CF(50),CR(2
40),BAPRES(20),TEST(20),SPARK(50),KNOCK(50),FUE(20),TE(50),AF(50),
5HYC(50),FUA(50),COM(50),MEN(50),TS(50),FUIHP(50),CYTEM(50),FUTEM(5
60),PRES(50)
  REAL LOAD, LB, IHP, N2, MASS, MEFF, MW, MEN
  INTEGER RUN, NO, I
  DD=500.0
  READ(5,99) M, PROPA
  DO 24 J=1,M
  READ(5,100)BAPRES(J),CR(J),TEST(J),NO,FRIC(J),FUEL(J),FUE(J)
  WRITE(6,104)
  WRITE(6,105)TEST(J),CR(J),FUEL(J),FUE(J),BAPRES(J),NO
  DO 1 I=1,NO
  READ(5,106)RUN(I),SPARK(I),REVS(I),TIME(I),FUTEM(I),PRES(I),TEMP(I
1),DP(I),TEM(I),CO2(I),O2(I),CO(I),LOAD(I),COM(I),MEN(I),TS(I)
  RPM(I)=REVS(I)/TIME(I)
1  CONTINUE
  IF(FUEL(J).EQ. PROPA) GO TO 3
  WRITE(6,102)
  DO 2 I=1,NO
2  WRITE(6,111) RUN(I),SPARK(I),REVS(I),TIME(I),TEMP(I),DP(I),TEM(I),
1CO2(I),O2(I),CO(I),LOAD(I),COM(I),MEN(I),TS(I)
  GO TO 5
3  WRITE(6,103)
  DO 4 I=1,NO
4  WRITE(6,112) RUN(I),SPARK(I),REVS(I),TIME(I),FUTEM(I),PRES(I),TEMP
1(I),DP(I),TEM(I),CO2(I),O2(I),CO(I),LOAD(I),COM(I),MEN(I),TS(I)
5  CONTINUE
  WRITE(6,113) FRIC(J)
  PRESS=(BAPRES(J)*14.696)/29.92
  IF(FUEL(J).EQ. PROPA) GO TO 7
C  FUEL IS GASOLINE
  X=7.
  Y=16.
  HV=19137.
  MW=100.198
  STOIC=.068
  DO 6 I=1,NO
C  FUEL CONSUMPTION (50 GRAMS)
  LB(I)=(0.050*2.2046*60.)/TIME(I)
6  CONTINUE
  GO TO 11

```



APPENDIX B

PROGRAM FOR CALCULATING THE FUEL CONSUMPTION OF A CAR

DATE: 10/10/2010  
PAGE: 1

1000  
1100  
1200

1300  
1400  
1500

1600  
1700  
1800  
1900  
2000  
2100  
2200  
2300  
2400  
2500  
2600  
2700  
2800  
2900  
3000  
3100  
3200  
3300  
3400  
3500  
3600  
3700  
3800  
3900  
4000  
4100  
4200  
4300  
4400  
4500  
4600  
4700  
4800  
4900  
5000  
5100  
5200  
5300  
5400  
5500  
5600  
5700  
5800  
5900  
6000  
6100  
6200  
6300  
6400  
6500  
6600  
6700  
6800  
6900  
7000  
7100  
7200  
7300  
7400  
7500  
7600  
7700  
7800  
7900  
8000  
8100  
8200  
8300  
8400  
8500  
8600  
8700  
8800  
8900  
9000  
9100  
9200  
9300  
9400  
9500  
9600  
9700  
9800  
9900  
10000

10100  
10200  
10300  
10400  
10500  
10600  
10700  
10800  
10900  
11000  
11100  
11200  
11300  
11400  
11500  
11600  
11700  
11800  
11900  
12000  
12100  
12200  
12300  
12400  
12500  
12600  
12700  
12800  
12900  
13000  
13100  
13200  
13300  
13400  
13500  
13600  
13700  
13800  
13900  
14000  
14100  
14200  
14300  
14400  
14500  
14600  
14700  
14800  
14900  
15000  
15100  
15200  
15300  
15400  
15500  
15600  
15700  
15800  
15900  
16000  
16100  
16200  
16300  
16400  
16500  
16600  
16700  
16800  
16900  
17000  
17100  
17200  
17300  
17400  
17500  
17600  
17700  
17800  
17900  
18000  
18100  
18200  
18300  
18400  
18500  
18600  
18700  
18800  
18900  
19000  
19100  
19200  
19300  
19400  
19500  
19600  
19700  
19800  
19900  
20000

20100  
20200  
20300  
20400  
20500  
20600  
20700  
20800  
20900  
21000  
21100  
21200  
21300  
21400  
21500  
21600  
21700  
21800  
21900  
22000  
22100  
22200  
22300  
22400  
22500  
22600  
22700  
22800  
22900  
23000  
23100  
23200  
23300  
23400  
23500  
23600  
23700  
23800  
23900  
24000  
24100  
24200  
24300  
24400  
24500  
24600  
24700  
24800  
24900  
25000  
25100  
25200  
25300  
25400  
25500  
25600  
25700  
25800  
25900  
26000  
26100  
26200  
26300  
26400  
26500  
26600  
26700  
26800  
26900  
27000  
27100  
27200  
27300  
27400  
27500  
27600  
27700  
27800  
27900  
28000  
28100  
28200  
28300  
28400  
28500  
28600  
28700  
28800  
28900  
29000  
29100  
29200  
29300  
29400  
29500  
29600  
29700  
29800  
29900  
30000

30100  
30200  
30300  
30400  
30500  
30600  
30700  
30800  
30900  
31000  
31100  
31200  
31300  
31400  
31500  
31600  
31700  
31800  
31900  
32000  
32100  
32200  
32300  
32400  
32500  
32600  
32700  
32800  
32900  
33000  
33100  
33200  
33300  
33400  
33500  
33600  
33700  
33800  
33900  
34000  
34100  
34200  
34300  
34400  
34500  
34600  
34700  
34800  
34900  
35000  
35100  
35200  
35300  
35400  
35500  
35600  
35700  
35800  
35900  
36000  
36100  
36200  
36300  
36400  
36500  
36600  
36700  
36800  
36900  
37000  
37100  
37200  
37300  
37400  
37500  
37600  
37700  
37800  
37900  
38000  
38100  
38200  
38300  
38400  
38500  
38600  
38700  
38800  
38900  
39000  
39100  
39200  
39300  
39400  
39500  
39600  
39700  
39800  
39900  
40000

40100  
40200  
40300  
40400  
40500  
40600  
40700  
40800  
40900  
41000  
41100  
41200  
41300  
41400  
41500  
41600  
41700  
41800  
41900  
42000  
42100  
42200  
42300  
42400  
42500  
42600  
42700  
42800  
42900  
43000  
43100  
43200  
43300  
43400  
43500  
43600  
43700  
43800  
43900  
44000  
44100  
44200  
44300  
44400  
44500  
44600  
44700  
44800  
44900  
45000  
45100  
45200  
45300  
45400  
45500  
45600  
45700  
45800  
45900  
46000  
46100  
46200  
46300  
46400  
46500  
46600  
46700  
46800  
46900  
47000  
47100  
47200  
47300  
47400  
47500  
47600  
47700  
47800  
47900  
48000  
48100  
48200  
48300  
48400  
48500  
48600  
48700  
48800  
48900  
49000  
49100  
49200  
49300  
49400  
49500  
49600  
49700  
49800  
49900  
50000

50100  
50200  
50300  
50400  
50500  
50600  
50700  
50800  
50900  
51000  
51100  
51200  
51300  
51400  
51500  
51600  
51700  
51800  
51900  
52000  
52100  
52200  
52300  
52400  
52500  
52600  
52700  
52800  
52900  
53000  
53100  
53200  
53300  
53400  
53500  
53600  
53700  
53800  
53900  
54000  
54100  
54200  
54300  
54400  
54500  
54600  
54700  
54800  
54900  
55000  
55100  
55200  
55300  
55400  
55500  
55600  
55700  
55800  
55900  
56000  
56100  
56200  
56300  
56400  
56500  
56600  
56700  
56800  
56900  
57000  
57100  
57200  
57300  
57400  
57500  
57600  
57700  
57800  
57900  
58000  
58100  
58200  
58300  
58400  
58500  
58600  
58700  
58800  
58900  
59000  
59100  
59200  
59300  
59400  
59500  
59600  
59700  
59800  
59900  
60000

```

C FUEL IS PROPANE GAS
7  X=3.
   Y=8.
   HV=19929.
   MW=44.098
   STOIC=0.064
   DO 10 I=1,NO
C FUEL CONSUMPTION IS 1/2 CUBIC FOOT
   GAPR=2.*PRES(I)*29.92/(33.899*12.0)
   IF(FUTEM(I).GT.70.) GO TO 8
   PSAT=(0.3631-(70.-FUTEM(I))*0.01068)*29.92/14.696
   GO TO 9
8  PSAT=(0.3631+(FUTEM(I)-70.)*0.01438)*29.92/14.696
9  PT=BAPRES(J)+GAPR-PSAT
   VOL=0.5*PT*520./((29.92*(FUTEM(I)+459.9))
   LB(I)=50.0*VOL/(8.503*TIME(I))
10 CONTINUE
11 CONTINUE
   DO 13 I=1,NO
C CORRECTION FACTOR (TO 29.90 IN HG. AND 85DEGREES F.)
   CF(I)=(29.90/BAPRES(J))*SQRT((459.9+TEMP(I))/545.0)
C TORQUE
   TOR(I)=10.52*LOAD(I)/12.0
C BRAKE HP
   BHP(I)=(2.0*3.14159*TOR(I)*RPM(I))/33000.0
C FRICTION HP
   FHP(I)=(2.*3.14159*RPM(I)*FRIC(J)*10.52)/(33000.*12.)
C INDICATED HP
   IHP(I)=(BHP(I)+FHP(I))*CF(I)
C CORRECTED BHP
   CBHP(I)=IHP(I)-FHP(I)
C INDICATED THERMAL EFFICIENCY
   ETA(I)=(IHP(I)*2545.0*100.0)/(HV*LB(I))
C MECHANICAL EFFICIENCY
   MEFF(I)=(CBHP(I)*100.)/IHP(I)
C FUEL PER IHP
   FUIHP(I)=LB(I)/IHP(I)
C FUEL CONSUMPTION PER CBHP
   FU(I)=LB(I)/CBHP(I)
C
C **FUEL TO AIR RATIO**
C MEASURED ( CORRECTION FACTOR APPLIED )
   DENS=(PRESS*144.0)/(53.34*(TEMP(I)+459.7))
   HEAD=(DP(I)*62.4)/(DENS*12.0)
   VEL=0.62*(SQRT(2.*32.2*HEAD))
   FLOW=(VEL*3.14259*(0.9983**2)*15.*DENS/144.)*CF(I)
   RATIO(I)=LB(I)/(FLOW*60.0)
C AIR TO FUEL RATIO
   AF(I)=FLOW*60./LB(I)
C FROM ORSAT ANALYSIS
   H2=0.51*CO(I)
   CH4=0.22
   TOTAL=CO2(I)+O2(I)+CO(I)+H2+CH4
   N2=100.000-TOTAL
   OXY=N2/3.76

```



```

C ZCXHY+OXY(O2)+N2(N2) = CO2(CO2)+CO+0.3(CH4)+O2(O2)+H2(H2)+N2(N2)+2H2O
C CARBON,OXYGEN,BALANCE
  Z(I)=(CO2(I)+CO(I)+0.22)/X
  MASS=(OXY+N2)*28.967
  FA(I)=(Z(I)*MW)/MASS
  E(I)=(FA(I)-RATIO(I))*100.0/RATIO(I)
C TO CALCULATE HYDROGEN CARBON RATIO
  XX=X*Z(I)
  W=2.00*(OXY-CO2(I)-CO(I)/2.0-0.22)
  YY=0.83+H2*2.0+2.0*W
  HYC(I)=YY/(12.0*XX)
  FUA(I)=(12.0*XX+YY)/MASS
C
C TO CALCULATE BRAKE MEAN EFFECTIVE PRESSURE
  ALNC=((3.14159*3.25**2)*0.375*RPM(I))/8.0
  BMEP(I)=(33000.0*BHP(I))/ALNC
  CMEP(I)=33000.0*IHP(I)/ALNC
13 CONTINUE
C
C ** TO SORT INTO DESCENDING VALUES OF FUEL AIR RATIO**
  LIM=NO-1
14 KNT=1
C INITIALIZE KNT IN EVENT ALL RATIOS IN ORDER
  DO 15 I=1,LIM
    IF(RATIO(I+1).LT.RATIO(I)) GO TO 15
C IF RATIO(I+1).GT.RATIO(I) INTERCHANGE THEM
    SORT=RATIO(I+1)
    SA=RUN(I+1)
    SB=RPM(I+1)
    SC=BHP(I+1)
    SD=FHP(I+1)
    SE=IHP(I+1)
    SF=TOR(I+1)
    SG=ETA(I+1)
    SH=MEFF(I+1)
    SI=TEM(I+1)
    SJ=FU(I+1)
    SK=FUIHP(I+1)
    SL=CMEP(I+1)
    SM=SPARK(I+1)
    SN=CF(I+1)
    SO=CBHP(I+1)
    SP=LOAD(I+1)
    SQ=COM(I+1)
    SQA=MEV(I+1)
    SQB=TS(I+1)
    SR=HYC(I+1)
    SS=FUA(I+1)
    ST=FA(I+1)
    SU=Z(I+1)
    SV=E(I+1)
    SW=AF(I+1)
    SX=CO2(I+1)

```





```
SY=O2(I+1)
SZ=CO(I+1)
SZA=LB(I)
RATIO(I+1)=RATIO(I)
RUN(I+1)=RUN(I)
RPM(I+1)=RPM(I)
BHP(I+1)=BHP(I)
FHP(I+1)=FHP(I)
IHP(I+1)=IHP(I)
TOR(I+1)=TOR(I)
ETA(I+1)=ETA(I)
MEFF(I+1)=MEFF(I)
TEM(I+1)=TEM(I)
FU(I+1)=FU(I)
FUIHP(I+1)=FUIHP(I)
CMEP(I+1)=CMEP(I)
SPARK(I+1)=SPARK(I)
CF(I+1)=CF(I)
CBHP(I+1)=CBHP(I)
LOAD(I+1)=LOAD(I)
COM(I+1)=COM(I)
MEN(I+1)=MEN(I)
TS(I+1)=TS(I)
HYC(I+1)=HYC(I)
FUA(I+1)=FUA(I)
FA(I+1)=FA(I)
Z(I+1)=Z(I)
E(I+1)=E(I)
AF(I+1)=AF(I)
CO2(I+1)=CO2(I)
O2(I+1)=O2(I)
CO(I+1)=CO(I)
LB(I+1)=LB(I)
RATIO(I)=SORT
RUN(I)=SA
RPM(I)=SB
BHP(I)=SC
FHP(I)=SD
IHP(I)=SE
TOR(I)=SF
ETA(I)=SG
MEFF(I)=SH
TEM(I)=SI
FU(I)=SJ
FUIHP(I)=SK
CMEP(I)=SL
SPARK(I)=SM
CF(I)=SN
CBHP(I)=SO
LOAD(I)=SP
COM(I)=SQ
MEN(I)=SQA
TS(I)=SQB
HYC(I)=SR
```





```

    FUA(I)=SS
    FA(I)=ST
    Z(I)=SU
    E(I)=SV
    AF(I)=SW
    CO2(I)=SX
    O2(I)=SY
    CO(I)=SZ
    LB(I)=SZA
    KNT=I
C   KNT GIVES LOCATION OF LAST INTERCHANGE
C   SUCCEEDING VALUES IN ORDER
15  CONTINUE
    IF(KNT.EQ.1) GO TO 16
C   IF KNT=1 ALL RATIOS IN ORDER
    LIM=KNT-1
    GO TO 14
16  CONTINUE
C
C   ** TO PRINT RESULTS **
    WRITE(6,114)
    WRITE(6,115)
    DO 17 I=1,NO
        WRITE(6,116)RUN(I),RATIO(I),RPM(I),SPARK(I),TUR(I),BHP(I),FHP(I),I
1HP(I),CF(I),CBHP(I),MEFF(I),LB(I),FUIHP(I),FU(I),CMEP(I),ETA(I),TE
2M(I)
17  CONTINUE
    WRITE(6,117)
    DO 18 I=1,NO
        WRITE(6,118)RUN(I),RATIO(I),HYC(I),FA(I),FUA(I),Z(I),E(I),AF(I),CO
1M(I),MEN(I),TS(I)
18  CONTINUE
C   *** FOR PLOTTING RESULTS***
    IF(NO.LT.5) GO TO 24
    NN=NO
C   TO PLOT CBHP, FHP AND IHP
    RAT=RATIO(1)
    LK=0
    DIF=20.
    T=0.0
    WRITE(6,119)
    DO 19 I=1,NN
        CALL PLOTTER (RATIO(I),CBHP(I),FHP(I),IHP(I),T,DIF,RAT,LK,STOIC,DD)
19  CONTINUE
C   TO PLOT CO2,O2 AND CO
    RAT=RATIO(1)
    LK=0
    DIF=5.0
    T=0.0
    WRITE(6,120)
    DO 20 I=1,NN
        CALL PLOTTER (RATIO(I),CO2(I),O2(I),CO(I),T,DIF,RAT,LK,STOIC,DD)
20  CONTINUE

```



```

C   TO PLOT TH. EFF., TORQUE AND LOAD
    RAT=RATIO(1)
    LK=0
    DIF=2.0
    T=0.0
    WRITE(3,121)
    DO 21 I=1,NN
    CALL PLOTTER (RATIO(I),ETA(I),TOR(I),LOAD(I),T,DIF,RAT,LK,STOIC,DD)
21  CONTINUE
C   TO PLOT MECH. EFF.,CYLINDER TEMP./10.0 ,AND CBMEP
    RAT=RATIO(1)
    LK=0
    DIF=0.8
    T=20.0
    WRITE(6,122)
    DO 22 I=1,NN
    CYTEM(I)=TEM(I)/10.0
    CALL PLOTTER (RATIO(I),MEFF(I),CYTEM(I),CMEP(I),T,DIF,RAT,LK,STOIC
1,DD)
22  CONTINUE
C   TO PLOT FUEL PER CBHP,FUEL PER IHP AND A/F FROM ORSAT ANALYSIS
    RAT=RATIO(1)
    LK=0
    DIF=100.
    T=20.0
    WRITE(3,123)
    DO 23 I=1,NN
    AIR(I)=10.0*FA(I)
    CALL PLOTTER (RATIO(I),FU(I),FUIHP(I),AIR(I),T,DIF,RAT,LK,STOIC,DD)
23  CONTINUE
24  CONTINUE
99  FORMAT(I3,A6)
100 FORMAT(F7.3,F6.2,2I3,F4.1,3A6)
101 FORMAT(1HJ,F7.3,F6.2,2I3,3A6)
102 FORMAT(1HJ,68HRUN SPARK REVS  TIME  AIR  DP CY TEM  CO2  O2  CO
1  LOAD  COMMENTS)
103 FORMAT(1HJ,79HRUN SPARK REVS  TIME  FUTEM PRES AIR  DP CY TEM  CO
12  O2  CO  LOAD  COMMENTS)
104 FORMAT(1H1,40X,17H CFR TEST RESULTS)
105 FORMAT(1HL,10X,9HTEST NO.  ,I3,5X,6H C.R.=,F6.2,5X,9H FUEL IS ,2A6,
14X,22H BAROMETRIC PRESSURE =,F7.3,10X,I3)
106 FORMAT(I2,I3,F6.0,F6.3,F4.0,F5.2,F4.0,F6.3,F6.0,F5.1,2F4.1,F5.1,3A
16,A4)
111 FORMAT(1HJ,I3,I5,1X,F6.0,F6.3,F4.0,F6.3,F6.0,F6.1,2F5.1,F6.1,3A6)
112 FORMAT(1HJ,I3,I5,1X,F6.0,F6.3,F5.0,F6.2,F4.0,F6.3,F6.0,F6.1,2F5.1,
1F6.1,3A6,A4)
113 FORMAT(1HJ,15X,14H FRICTION LOAD=,F5.1,5H LBS.)
114 FORMAT(1HK,40X,13H** RESULTS **)
115 FORMAT(1HJ,25HRUN F/A(MEAS  RPM  SPARK,2X,45HTORQUE  BHP  FH
1P  IHP  CF  CBHP,2X,8HMECH EFF,2X,21HFU/HR FU/IHP  FU/CBH
2P,3X,23HIMEP  THER EFF CYL TEMP)
116 FORMAT(1HJ,I3,F8.4,F8.1,I4,2X,6F8.3,F7.2,3X,2F6.3,F8.3,3X,F7.2,F8.
12,3X,F6.0)

```





```
117 FORMAT(1HK,51H RUN F/A MEAS  H/C    F/A CAL  F/A CAL MOLES  ERROR,  
    110H A/F RATIO,8X,8HCOMMENTS)  
118 FORMAT(1HJ,I3,5F8.4,2F8.2,5X,3A6,A4)  
119 FORMAT(1H1,10X,38HCBHP,FHP,AND IHP VERSUS FUEL AIR RATIO)  
120 FORMAT(1H1,10X,37H CO2, O2 AND CO VERSUS FUEL AIR RATIO)  
121 FORMAT(1H1,10X,53H THERMAL EFF., TORQUE AND LOAD VERSUS FUEL AIR  
    1RATIO)  
122 FORMAT(1H1,10X,53H MECH EFF, CYL TEMP/10 AND CBMEP VERSUS FUEL AIR  
    1RATIO)  
123 FORMAT(1H1,10X,67HFUEL PER CBHP, FUEL PER IHP AND FUEL AIR RATIO F  
    1ROM ORSAT ANALYSIS )  
    STOP  
    END
```





```

$IBFTC PLOTTER DECK
      SUBROUTINE PLOTTER(X,Y,R,S,T,DIF,RAT,LK,STOIC,DD)
      DIMENSION CHAR(99)
      DATA BLANK,PLOTY,PLOTR,PLOTS/1H ,1H*,1H+,1HX/
      IF(LK.GT.0) GO TO 1
      IF(RAT.GT.STOIC) GO TO 1
      WRITE(6,7) STOIC
1     CONTINUE
      LK=1
      IF(RAT.LE.STOIC) GO TO 5
      IF(X.GT.STOIC) GO TO 5
      KK=(RAT-STOIC)*DD+.5
      DO 2 L=1, KK
2     WRITE(5,3)
      WRITE(6,7) STOIC
      RAT=STOIC
5     CONTINUE
      DO 6 JK=1,99
6     CHAR(JK)=BLANK
      KK=(RAT-X)*DD+.5
      I=Y*DIF-T
      J=R*DIF-T
      K=S*DIF-T
      IF(I.LE.99) GO TO 10
      I=99
10    IF(I.GT.0) GO TO 11
      I=1
11    IF(J.LE.99) GO TO 12
      J=99
12    IF(J.GT.0) GO TO 13
      J=1
13    IF(K.LE.99) GO TO 14
      K=99
14    IF(K.GT.0) GO TO 15
      K=1
15    CONTINUE
      IF(J.EQ.I) J=I+1
      IF(K.EQ.J) K=J+1
      IF(K.EQ.I) K=I+1
      CHAR(I)=PLOTY
      CHAR(J)=PLOTR
      CHAR(K)=PLOTS
      DO 8 L=1, KK
8     WRITE(6,3)
      WRITE(5,4) X,Y,R,S,CHAR
      RAT=X
3     FORMAT(1HJ)
4     FORMAT(1H ,F8.4,3F7.2,1X,1H.,99A1)
7     FORMAT(1HJ,F8.4,23H STOICHIOMETRIC MIXTURE,10(1H.,9X))
9     RETURN
      END
$ENTRY          POND

```



## APPENDIX F

SAMPLE SET OF RESULTSCFR TEST RESULTS

TEST NO. 5 C.R. = 9.82 FUEL IS PROPANE

\*\* RESULTS \*\*

REV	F/A(M-FAS)	RPM	SPARK	TORQUE	CHP	FHP	IHP	CF
48	0.0574	603.0	5	20.865	2.398	0.977	3.662	1.085
49	0.0501	604.9	5	21.829	2.514	0.979	3.797	1.087
50	0.0413	594.4	5	20.514	2.321	0.962	3.569	1.087
51	0.0320	600.1	10	15.342	1.753	0.972	2.964	1.088
52	0.0254	596.6	20	8.665	0.716	0.966	2.048	1.088

CHP	MECH EFF	FU/HR	FU/IHP	FU/CHP	IMEP	THER EFF	CYL TEMP
2.665	73.31	1.670	0.456	0.622	128.71	27.99	803.
2.818	74.21	1.448	0.381	0.514	133.18	33.50	856.
2.607	73.04	1.193	0.334	0.457	127.41	38.22	830.
1.992	67.22	0.938	0.316	0.471	104.79	40.36	703.
1.082	52.83	0.753	0.368	0.696	72.82	34.71	535.







**B29857**